AD-A061 107 PURDUE UNIV LAFAYETTE IND PROJECT SQUID HEADQUARTERS F/G 21/8
PROJECT SQUID.(U)
OCT 78 T C ADAMSON, M SICHEL, E P BRUCE N00014-75-C-1143

UNCLASSIFIED NL

1 OF 2
ADA
061107

LEVEL II

12

AD A061107

PROJECT SQUID

SEMI-ANNUAL PROGRESS REPORT

1 OCTOBER 1978

AEROCHEM RESEARCH LABORATORIES, INC.
AERONAUTICAL RESEARCH ASSOCIATES OF PRINCETON, INC.
CALIFORNIA INSTITUTE OF TECHNOLOGY
UNIVERSITY OF CALIFORNIA, SAN DIEGO
COLORADO STATE UNIVERSITY
UNIVERSITY OF COLORADO
CORNELL UNIVERSITY
KANSAS STATE UNIVERSITY
GENERAL ELECTRIC COMPANY
UNIVERSITY OF MICHIGAN
UNIVERSITY OF MISSOURI
PENNSYLVANIA STATE UNIVERSITY
POLYTECHNIC INSTITUTE OF NEW YORK
PRINCETON UNIVERSITY
UNIVERSITY OF SHEFFIELD
UNIVERSITY OF SOUTHERN CALIFORNIA
SOUTHERN METHODIST UNIVERSITY
STANFORD UNIVERSITY
UNITED TECHNOLOGIES RESEARCH CENTER
VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY
UNIVERSITY OF WASHINGTON
YALE UNIVERSITY

PROJECT SQUID HEADQUARTERS
CHAFFEE HALL
PURDUE UNIVERSITY
WEST LAFAYETTE, INDIANA

Project SQUID is a cooperative program of basic research relating to Jet Propulsion. It is sponsored by the Office of Naval Research and is administered by Purdue University through Contract N00014-75-C-1143, NR-098-038.

10 T. C. /Adamson, Jr., M. /Sichel,
Edgar P. /Bruce, Franklin O. /Carta
F. B. /Gessner

SEMI-ANNUAL PROGRESS REPORT

6 PROJECT SQUID.

A COOPERATIVE PROGRAM OF FUNDAMENTAL RESEARCH
RELATED TO JET PROPULSION
OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY

THIS REPORT COVERS THE WORK ACCOMPLISHED
DURING THE PERIOD 1 OCTOBER 1977 TO MARCH 31, 1978
BY PRIME AND SUBCONTRACTORS UNDER
CONTRACT N00014-75-C-1143, NR-098-038

15

12 106p.

11 1 OCTOBER 1978

9 Semi-annual progress rept. 1 Oct 77-31
Mar 78,

PROJECT SQUID HEADQUARTERS
CHAFFEE HALL
PURDUE UNIVERSITY
WEST LAFAYETTE, INDIANA 47907

TABLE OF CONTENTS ;

I. AERODYNAMICS AND TURBOMACHINERY

Semi-Annual Progress Report

THREE DIMENSIONAL TRANSONIC FLOWS IN COMPRESSORS AND CHANNELS

The University of Michigan, Ann Arbor, Michigan
Subcontract No. 8960-10

Professor T.C. Adamson, Jr., Principal Investigator
Professor M. Sichel, Principal Investigator

Introduction

The general goal of this program is the application of asymptotic methods of analysis to the study of transonic flows through a compressor blade row. Of particular interest is that case where conditions are such that a sonic cylinder is found in the incoming flow relative to the blades; then the flow through the blades is mixed supersonic-subsonic and a two dimensional approximation is not adequate. Previous studies in this program have dealt with a model flow problem of transonic shear flow through a three dimensional channel.[1,2] In this model problem, the important physical effects were retained, but in a very simple geometry so that some understanding of the flow problem could be gained with as little complexity as possible. These studies have been completed and will be reported soon. The work to be described here is the extension of the analysis to cover the actual rotor flow.

Discussion

A very important aspect of the problem under consideration is the definition of the limit process to be used in performing the asymptotic analysis. That is, it is important that the limit process chosen be such that the small parameters used in the analysis actually correspond to physical parameters in a range of technical interest. Other authors have applied asymptotic methods to flows in turbomachinery (e.g., references 3 and 4). In these cases, the small parameter was taken to be the inverse of the number of blades; in the limit as this small parameter goes to zero, the resulting solutions are those for the so-called through-flow. Here, it is desired to take advantage of the fact that the flow relative to the blades is near sonic velocity and the fact that the blades are thin. It turns out, then, that two small parameters must be considered, one being the inverse of the number of blades and the new small parameter being the dimensionaless axial chord of the blade, $c_a = \bar{c}_a \bar{\omega} / \bar{a}_o$, where $\bar{c}_a$, $\bar{\omega}$, and $\bar{a}_o$ are the dimensional axial blade chord, the angular velocity, and the speed of sound in the incoming flow, respectively. A typical value for c_a is 0.1, so c_a may indeed be considered a small parameter.

The analysis is being formulated so that blades with spanwise variations in airfoil shape and chord and axial variations in span may be accommodated. The first calculations are being made for very simple shapes, however, and these calculations result in very simple first order solutions for the flow between the blades. In this regard, the solutions are very similar to those found in the model flow solutions.[1] However, upstream and downstream of the blades there are no channel walls; the flow region in question is, then, the channel like flow between stagnation stream surfaces, and the solutions are much more difficult. Thus, in these regions the shape of the stagnation streamlines which form the "channel" walls must be found as part of the solution. It is this problem which is under study at the present time.

When the flow relative to the blades is supersonic, with a Mach number that is large enough, the bow shock waves off the leading edge of a blade bend back as they propagate through flow ahead of the blade row until they are parallel to the rotor. In transonic flow, as the Mach number approaches unity, this occurrence is no longer possible, but the waves become weaker. As a result, the air entering the blade row may be traversed by many very weak waves which are further weakened both by expansion fans from the suction surfaces of

the blades and by viscous effects. It is important to be able to analyze this flow field so that the entropy change across the waves may be ascertained, and the mass flow through the blade row may be calculated. It is this flow field upstream of the blades which is being studied at the present time. The case being considered is that where the flow relative to the blades is everywhere supersonic; next, the subsonic flow case and finally the mixed flow case will be analyzed.

References

1. Adamson, Jr., T.C., "Three Dimensional Transonic Shear Flow in a Channel," Transonic Flow Problems in Turbomachinery, Eds., Adamson, Jr., T.C. and Platzer, M.F., Hemisphere Publishing Corporation, Washington, D.C., 1977, pp. 70-78.

2. Sichel, M. and Adamson, Jr., T.C., "Three Dimensional Transonic Flows in Channels," presented at 13th Bienniel Fluid Dynamics Symposium, 5-10 September 1977, Olsztyn, Poland.

3. Guiraud, J.P. and Zeytounian, R.K., "Sur la Structure des E'coulements Tourbillonnaires dan les Turbomachines Axiales," La Rech. Aeron. No. 1971-2, pp. 65-87.

4. Veuillot, J.-P., "Calculation of the Quasi Three Dimensional Flow in a Turbomachine Blade Row," J. of Engineering for Power, 99 (A) No. 1, Jan., 1977, pp. 53-62.

AXIAL FLOW FAN STAGE UNSTEADY PERFORMANCE

Applied Research Laboratory
The Pennsylvania State University
P. O. Box 30, State College, Pennsylvania 16801

Subcontract No. 8960-4

Edgar P. Bruce, Principal Investigator

Introduction

The objective of this research is to analyze the time-dependent interaction between the components of an isolated axial flow fan stage and a spatially fixed, circumferentially varying flow field. The major variables are reduced frequency; rotor blade space-to-chord ratio, stagger angle, mean angle of attack, and design loading level; and rotor-stator axial spacing.

The experiments are being conducted in the ARL Axial Flow Research Fan. This facility has a hub radius of 12.06 cm (4.75 inches), a hub-to-tip radius ratio of 0.442, and operates in the subsonic incompressible flow regime. The rotor and stator blades have a 10 percent thick C1 profile with a chord of 15.24 cm (6.00 inches) and an aspect ratio of unity.

Instrumentation available at present or under development consists of: (1) a strain gaged sensor mounted within one rotor blade which detects the time-dependent normal force and pitching moment developed on a mid-span blade segment, (2) hot-film sensors mounted on the suction surface of rotor and stator blades which detect the nature of the boundary layer, i.e., whether the instantaneous boundary layer flow is laminar, turbulent or separated; (3) dynamic total head probes; (4) two-element hot-film probes; and (5) conventional three-dimensional directional probes. A system is being developed which will permit on-line analysis of all time-dependent signals by a digitizing, phase-lock averaging process.

The unsteady normal force and pitching moment results obtained in the initial phase of this program at reduced frequencies from 0.2 to 2.1 have been documented in a Project SQUID report (Reference 1). Since completing the initial phase, our efforts have been directed toward extending the reduced frequency range of the uncambered rotor experiments (Reference 1) [illegible] 2.1 to 5.0, and toward a detailed examination of the effects of inflow [illegible]n on the performance of a stage designed with a free-vortex lo[illegible]tribution. A related theoretical effort has as its goal an exten[illegible]f the unsteady lift cascade model developed by Henderson (Refer[illegible] 2) to include the unsteady pitching moment.

Discussion

During this reporting period, we have made progress in both the experimental and theoretical areas. With respect to the experimental tasks, we have:

1) Completed shakedown testing of a "Galton Whistle" type standing wave tube for use in the calibration of dynamic pressure sensors and sensor/mounting assemblies. This device operates over the frequency range from 200 to 5000 Hz with peak pressure amplitudes to 2.5 psi

2) Completed the design of a dynamic total pressure probe. The probe consists of a miniature piezoresistive pressure transducer mounted in the body of a commercially available Kiel probe. Provisions have been made to utilize the standing wave tube for calibration of the pressure transducer and for evaluation of the dynamic characteristics of the transducer/probe assembly, and

3) Reduced data obtained using conventional 5-hole probes located immediately upstream of and approximately one-half chord length downstream of cambered and uncambered isolated rotors operating at low and high loading levels over the reduced frequency range from 0.2 to 5.0. These data define the circumferential variation of time mean values of total and static pressure and axial, radial and circumferential velocity. Conclusions based upon analysis of these data are;

   a) rotor performance in distorted inflow, as measured by the mean total pressure rise, can be accurately predicted by the uniform inflow performance curve if the mean flow coefficient is used to characterize the distorted inflow,

   b) attenuation of the distorted inflow occurs as the flow approaches the rotor inlet and as it proceeds through the rotor -- the attenuation through the rotor can be much stronger than the inlet attenuation, and

   c) a ratio of rotor blade spacing-to-distortion wavelength exists for which the distortion attenuation is maximized -- this ratio is independent of mean incidence angle and camber for the values included in this investigation.

The theoretical effort has been devoted to development of an expression for the unsteady pitching moment using the cascade vortex model employed by Henderson (Reference 2) in his derivation of an expression for unsteady cascade lift. The moment equation has been derived and is being programmed for use on the IBM 360 at present.

References

1. Bruce, E. P. and Henderson, R. E., "Axial Flow Rotor Unsteady Response to Circumferential Inflow Distortions," Project SQUID Technical Report PSU-13-P, September 1975.

2. Henderson, R. E., "The Unsteady Response of an Axial Flow Turbomachine to an Upstream Disturbance," Ph.D. Dissertation, Engineering Department, University of Cambridge, 1972.

INVESTIGATION OF THE EFFECTS OF HIGH AERODYNAMIC LOADING ON A CASCADE OF OSCILLATING AIRFOILS

United Technologies Research Center
East Hartford, Conn. 06108
Subcontract 8960-19

Franklin O. Carta, Principal Investigator
Arthur O. St. Hilaire, Principal Investigation

Introduction

The basic objective of this research program is to study the effect of aerodynamic loading on a cascade of oscillating airfoils. Measurements are being made of the unsteady chordwise pressure distribution for incidence angles up to $\alpha_{mcl} = 10$ deg, reduced frequencies up to k = 0.193, and over a range of interblade phase angle from $\sigma = -60$ deg to + 60 deg. These data are being used to calculate the unsteady stability parameters of the system including unsteady pitching moment coefficient and aerodynamic damping parameter.

Program Review

Tests have now been completed for both $\alpha_{mcl} = 6$ deg and 10 deg and these data have been combined with data obtained previously at $\alpha_{mcl} = 8$ deg to provide a comprehensive picture of the effects of all parameters on blade stability. For the range of parameters tested it was found that the interblade phase angle is the single most important parameter affecting the stability of oscillating cascaded airfoils. The system is unstable for most positive values of σ over the entire range of loading and frequency. This is in conflict with the predictions of available potential flow cascade theories (e.g., Refs. 1, 2) and supports the observation that blade stall need not be present for torsional "stalled" flutter to occur (Ref. 3). System stability at negative values of σ was more dependent on loading and frequency and appears to conform more closely to the concept of stalled flutter. Specifically, for $\sigma<0$ deg the level of stability increases with frequency and decreases with loading. A preliminary evaluation of the pressure time histories shows that a second harmonic behavior renders the 1.2 percent chord station ineffective in contributing to the blade damping, and most of the damping is associated with the lead or lag of the first harmonic component of pressure at the 6.2 percent chord station.

Data reduction is ongoing and a report and a paper are now being written on the work done to date. Preparations are being made to re-enter the tunnel to examine the effect of varying the gap/chord ratio at a single value of α_{mcl} over a range of k and σ. At the conclusion of this test program a comprehensive examination of all the data taken to date will be initiated in an effort to understand the underlying causes of the phenomena observed. Particular attention will be focused on the blade leading edge region and the suspected interaction mechanism with adjacent blades.

References

1. Whitehead, D.S.: Force and Moment Coefficients for Vibrating Aerofoils in Cascade. A.R.C. R.&M. No. 3254, 1962.

2. Smith, S. N.: Discrete Frequency Sound Generation in Axial Flow Turbomachines. A.R.C. R.&M. No. 3709, 1971.

3. Mikolajczak, A. A., R. A. Arnoldi, L. E. Snyder, H. Stargardter: Advances in Fan and Compressor Blade Flutter Analysis and Predictions. AIAA Journal of Aircraft, vol. 12, no. 4, April 1975, pp. 325-332.

INVESTIGATION OF ADVERSE PRESSURE GRADIENT CORNER FLOWS

University of Washington, Seattle, Washington
Subcontract No. 8960-27

Professor F.B. Gessner, Principal Investigator
Mr. M.T. Littlefield, Research Assistant

Introduction

This project is concerned with the acquisition and analysis of data obtained in the vicinity of a streamwise corner under adverse pressure gradient flow conditions. The purpose of the study is to provide a body of data which can serve as a testing ground for turbulence models applicable to three-dimensional slender shear flows and give insight into the behavior of local flow variables in the vicinity of a corner under decelerating flow conditions. The data include measurements of both the primary (axial) and secondary (transverse) mean flow and components of the Reynolds stress tensor. Flow visualization studies will also be pursued in order to provide qualitative information on local corner flow behavior at, and near, incipient separation. The time schedule for implementation of the above objectives has been offset by time which has been spent in analyzing response behavior of hot-wires under skewed flow conditions. This course of action was pursued before initiating corner flow measurements because: (1) it was anticipated that conventional (zero-order) response equations would not be adequate for analyzing Reynolds stress data in the presence of relatively strong secondary flows which exist in the near corner region and (2) it was felt that previously developed first- and second-order response equation models were simply not adequate for analyzing the data.

Discussion

Hot-Wire Response Study The results of the response equation model we have developed are summarized in a previous progress report [1] and are described in more detail in a recently published thesis [2]. A comprehensive report on the work is now being prepared [3] which will include a detailed development

of the response equations and additional results not reported previously.

Corner Flow Study As the hot-wire response study was nearing completion, final preparations were made for initiating corner flow measurements in a variable divergence angle rectangular diffuser ($0\leq 2\phi \leq 30°$) with an 8:1 inlet aspect ratio. This diffuser was previously used in a study of the effect of a wall jet on diffuser performance [4], and it was necessary to eliminate a slot on each diverging wall for the purposes of the present study. This was accomplished by remachining the slot configuration, aligning the surfaces immediately upstream and downstream of the slot, and using an epoxy filler to form a continuous surface. This modification proved to be unsatisfactory, however, because whenever the divergence angle was changed significantly, a crack would develop at the slot location. Rather than attempting to make measurements under these conditions, a new diffuser configuration was designed with a single plate for each diverging wall having a series of kerf-like notches, so that the downstream sections of the plates could be set at different divergence angles while maintaining the upstream (inlet) sections parallel to each other. These plates are presently being machined, and modifications to the present facility should be completed shortly.

During the present reporting period a traversing mechanism for positioning probes at the diffuser inlet was designed and constructed. The traversing mechanism located at the exit plane of the diffuser was also modified in order to locate probes in any transverse (y-z) plane to within a resolution accuracy of ± 0.001 inch in both the y- and z-directions. This mechanism can now be located on either side of the diffuser so that it lies completely outside the flow. A probe holder with variable offset capability has been constructed which minimizes possible probe support blockage effects in the corner region. Pressure probes have been built for the purpose of making local wall shear stress and total pressure measurements in the corner region. Hot-wire probes for flow direction and Reynolds stress measurements are available from previous studies. These measurements will commence as soon as modifications to the diffuser are completed.

References

1. Gessner, F.B., and Ono, S.T.*, "Investigation of Adverse Pressure Gradient Corner Flows," Semi-Annual Progress Report, Project SQUID, April 1978, pp. 11-14.

2. Littlefield, M.T., "Investigation of Hot-Wire Response Characteristics in Skewed Mean Flow," M.S. Thesis, Department of Mechanical Engineering, University of Washington, 1978.

*The name "S.T. Ono" was legally changed to "M.T. Littlefield" on July 21, 1978.

3. Gessner, F.B., "Response Behavior of Hot-Wires in Skewed Mean Flow," Technical Report UW-1-PU, Project SQUID, 1978 (in preparation).

4. Fiedler, R.A., and Gessner, F.B., "Influence of Tangential Fluid Injection on the Performance of Two-Dimensional Diffusers," Journal of Basic Engineering, Trans. ASME, Series D, Vol. 94, No.3, 1972, pp. 666-674.

TRANSITORY STALL IN DIFFUSERS

Thermosciences Division
Department of Mechanical Engineering
Stanford University
Stanford, California 94305
Subcontract No. 8960-24

Professor James P. Johnston, Principal Investigator
Professor Stephen J. Kline, Principal Investigator
Mr. Jalal Ashjaee, Research Assistant
Mr. John Eaton, Research Assistant

Introduction

The general goal of this program is to study the transitory stall flow regime in two-dimensional diffusers. Maximum value of pressure recovery at fixed *non-dimensional* length, an important design optimum [1], generally occurs when the turbulent boundary layers are starting to separate or stall. The flow is rather unsteady and significant amounts of transient back flow already are seen in the diffuser at peak pressure recovery. These flow conditions are associated with the onset and development of the transitory stall flow regime [2].

Ghose and Kline [3] have developed a new, steady flow boundary layer prediction method which is solved simultaneously (not iteratively) with the inviscid core flow. This method gives surprisingly good agreement with data on pressure recovery up to, and slightly beyond the condition of peak recovery. The existing wall pressure data in this region are not of sufficient accuracy to properly check the method, however.

The primary objectives of our program are (i) to provide new mean and fluctuation velocity and pressure data in diffusers operating close to peak pressure recovery in order to complement, check and provide a data base of sufficient accuracy to allow for possible improvement of the prediction method of Ghose and Kline [3], and (ii) to study the magnitude of the velocity and pressure fluctuations in the transitory stall regime in order to provide a useful extension of the work of Smith and Kline [2] and Layne and Smith [4].

Discussion

Work is proceeding in the following areas, (i) the evaluation of the UIM method [3] for the diffuser of $L/W_1 = 15$ under the test conditions, (ii) the collection of data for the per cent of backflow near detachment for various selected diffuser opening angles using the wall-layer flow direction sensor, (iii) the reduction of contour maps for spanwise total pressure distribution at selected locations of S/W_1, and (iv) the addition of a pressurizing system to the diffuser tunnel in order to be able to control the tunnel pressure level along with planning for the measurement of the fluctuating quantities.

Diffuser Experiments for the first set of mean pressure distribution along the walls are now complete. In this set of tests, the measurements of wall pressure were carried for the diffuser of $L/W_1 = 15$ at selected total included angles (2θ) of 4, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, and 24 degrees where, in all cases the geometry was symmetric ($\theta_A = \theta_B$). Detailed results are given in the renewal proposal for this contract (July 1978). The inlet boundary layer integral parameters for these tests, based on measurements of velocity profiles at six different inlet locations ($S/W_1 = -1.14$), are shown in Table 1. Coles' integrals [5] have been employed in calculating the boundary layer thicknesses δ^*, and θ_1 reported in this table.

Table 1 - Boundary Layer Integral Parameters at Inlet

Integral Parameter	Uncorrected		Corrected	
	Mean	Deviation	Mean	Deviation
δ_1, B. L. Thickness (in.)	0.337	±.036	0.338	±.036
δ_1^*, Displacement Thickness (in.)	0.039	±.002	0.040	±.002
θ_1, Momentum Thickness (in.)	0.029	±.002	0.030	±.002
$H_1 = \delta_1^*/\theta_1$, Shape Factor	1.335	±.018	1.348	±.019

Fig. 1a and 1b show the experimental results for C_p along with the results of two prediction codes: the dashed lines in these figures are the original Ghose and Kline prediction [3] for each diffuser under the test

conditions, while the solid lines are the recently-modified version of the UIM method to include the end-wall blockage effect. As expected, this latter code gives better agreement with the experiment (the end-wall blockage effect would become specially important for inlet aspect ratios less than 4). Both codes, however, lose their capabilities as large transitory stall is approached (the UIM method is applicable up to $2\theta/2\theta_{a-a} = 1.2$) . For the present diffuser, the predictions fail beyond $2\theta \approx 10°$, as is apparent from results in Fig. 2 where the overall pressure recoveries are compared to test results. The solid lines in Fig. 2 are spline-fits to the data, the dash line is drawn from the data map of Reneau et al. [7] for an inlet blockage of $2\delta^*/W_1 = 0.03$, and the Ghose and Kline original and modified predictions are shown with dotted and dotdashed lines respectively.

An interesting phenomenon discovered in the experiments for included angles of 16, 20, and 24 degrees was what we called the "stall switch". A word on this has been said in the renewal proposal, however, the matter needs further investigation before we are able to give a complete, systematic report on this phenomenon. In the mean time, we have found that the pressure distributions for the stalled and unstalled walls remain unchanged no matter on which physical wall the stall is fixed; the pressure distributions switch from wall A to wall B when the stall pattern switches.

Work is in progress to obtain data on the per cent of backflow (the fraction of time that the flow is in upstream direction) in the detachment zone in order to achieve a better understanding of the flow and of the unsteady detachment phenomena [6]. An attempt will also be made to compare these data with the Sandborn and Kline criteria [8].

References

1. Sovran, G. and Klimp, E. D., "Experimentally Determined Optimum Geometries for Rectilinear Diffusers with Rectangular, Conical or Annular Cross-Sections," Fluid Mechanics of Internal Flow, G. Sovran, Editor, Elsevier Publishing Co., 1967, pp. 270-319.

2. Smith, C. R., Jr. and Kline, S. J., "An Experimental Investigation of the Transitory Stall Regime in Two-Dimensional Diffusers Including the Effects of Periodically Disturbed Inlet Conditions," J. of Fluids Engineering, TASME, Vol. 96(I), pp. 11-15, 1974.

3. Ghose, S. and Kline, S. J., "Prediction of Transitory Stall in Two-Dimensional Diffusers," Report MD-36, Thermosciences Division, Mechanical Engineering Dept., Stanford University, December 1976.

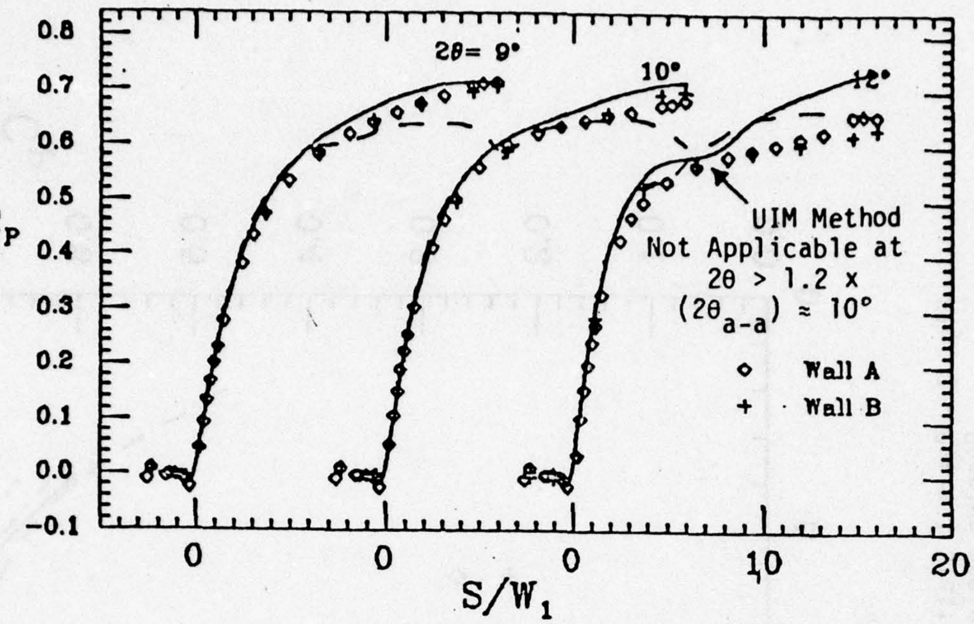
4. Layne, J. L. and Smith, C. R., Jr., "An Experimental Investigation of Inlet Flow Unsteadiness Generated by Transitory Stall in Two-Dimensional Diffusers," Tech. Report CFMTR 76-4, School of Mechanical Engineering, Purdue University, August, 1976.

5. Coles, D. E. and Hirst, E. A., Editors, Computation of Turbulent Boundary Layers - 1968, AFOSR-IFP-Stanford Conference, Vol. II, Thermosciences Division, Mechanical Engineering Dept., Stanford University, 1969.

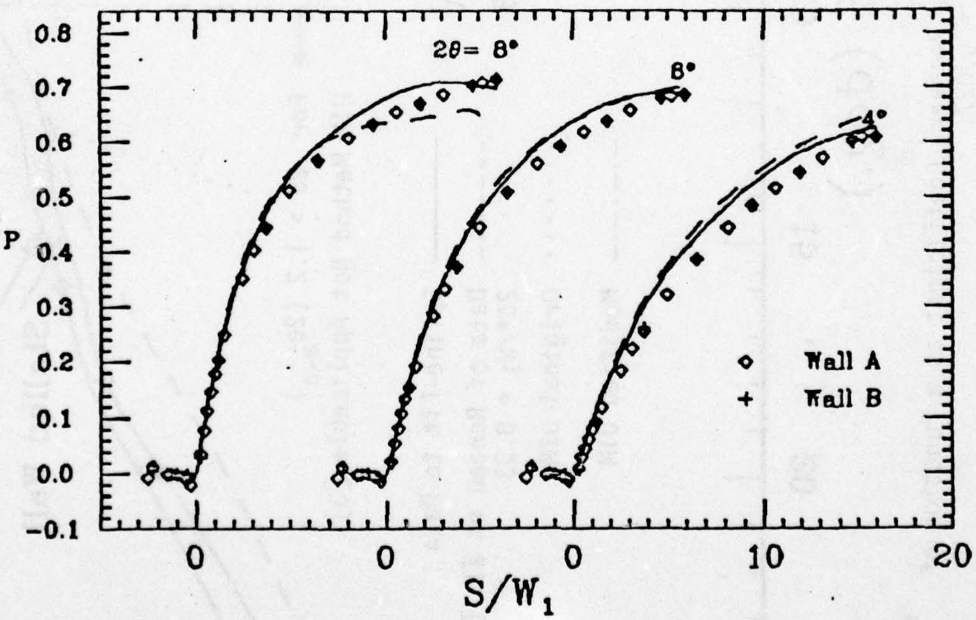
6. Johnston, J. P., "High Performance Design of Critical Fluid System Elements," Notes for Short Course 78-2, Fluid Dynamics Institute, Dartmouth College, Hanover, New Hampshire, August 28-September 1, 1978.

7. Reneau, L. R., Johnston, J. P. and Kline, S. J., "Performance and Design of Straight, Two-Dimensional Diffusers," J. Basic Engineering, Vol. 89, No. 1, pp. 141-150, March 1967.

8. Sandborn, V. A. and Kline, S. J., "Flow Models in Boundary Layer Stall Inception," J. Basic Engineering, Vol. 83, No. 3, pp. 317-327, Sept. 1961.



(1a)



(1b)

Fig. 1a and 1b - Wall Static Pressure Coefficient as a Function of Distance along the Wall. ——— : Original UIM, ——: Modified UIM.

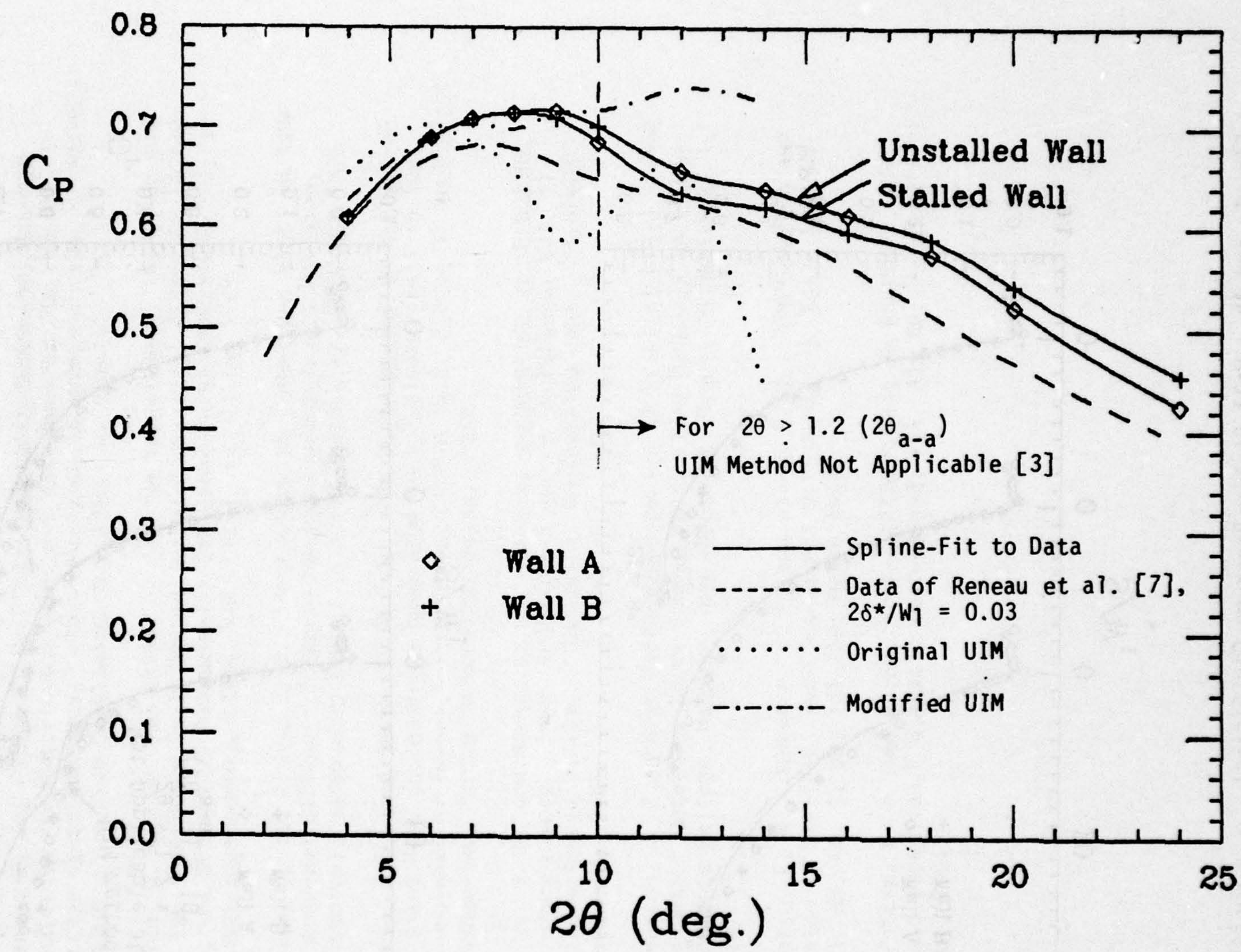


Fig. 2 - Overall Static Pressure Recovery Coefficient as a Function of Opening Angle. $2\delta^*/W_1 = 0.027$.

AN INVESTIGATION OF PRESSURE FLUCTUATIONS AND STALLING CHARACTERISTICS ON ROTATING AXIAL-FLOW COMPRESSOR BLADES

Virginia Polytechnic Institute
and State University, Blacksburg, Virginia
Subcontract No. 8960-13

Professor H. L. Moses, Principal Investigator
Professor W. F. O'Brien, Jr., Principal Investigator
Mr. R. R. Jones, Research Assistant
Mr. W. F. Siedlecki, Research Assistant

Introduction

The overall goal of this research program is to provide a better understanding of stall-related phenomena in axial-flow compressors. The aspects of compressor performance that are of interest include the onset of stall, loss in performance, and the flow instabilities associated with stall.

The program involves both experimental and analytical efforts. A primary feature of the experimental work is the measurement of pressures directly on the rotor of test compressors, for flow conditions up to and including stall. For high-frequency-response measurements, special radio telemetry data transmission equipment has been developed for use with blade-mounted transducers. Average and slowly-varying pressure measurements are made employing a pressure scanner that has been adapted to rotate with the compressor rotor. Ports on the compressor blades are connected by tubing to the scanning valve, and measurements are made by a single transducer located at the shaft center.

Experimental work is conducted employing a low-speed, single stage research compressor operating at approximately 2400 rpm, and a recently-completed high-speed drive facility. A three-stage research compressor designed for operation in the 13000-17000 rpm range has been readied for use in this facility.

During the present reporting period, work was completed on the initial formulation of a flow calculation method including viscous effects and stall in turbomachinery blade passages. The central feature of the method is the simultaneous calculation of an inviscid core and an integral boundary layer flow model. The method was adapted for a blade-to-blade calculation for a compressor blade row, to predict turning angle and losses associated with the row. An initial comparison of the theory with experimental cascade results was made. Additions were made to the high-speed research compressor facility, and a six-channel data coupling device was installed on a low-speed compressor for transmission of data from rotor blades in support of a planned experiment to determine rotor blade response to stalling disturbances.

Discussion

A method for the calculation of diffusing flows including viscous effects and stalling behavior has been developed [1]. Work has been progressing to adapt the method for prediction of blade-to-blade flows within compressor cascades. During the present reporting period, a computer program including the new flow model has been completed and run for a cascade composed of double-circular-arc blades. The calculation technique treats the core flow in the cascade as inviscid, and utilizes an integral model for the turbulent boundary layer. A finite-difference, simultaneous calculation technique provides for a stable, convergent prediction of flow within the cascade, flow exit angle, and losses. Predictions of the analysis have been compared with experiments in a stationary cascade with encouraging results. The program is now regarded as complete and operating, and additional work will constitute improvements in the area of boundary layer profile models, improved turbulence correlations, and improving the modeling of the loss mechanisms in the near wake region. A Ph.D. dissertation involving the development of the flow model and the programming is nearing completion, and a paper describing the boundary layer profile aspects of the calculation is in preparation. Comparisons of the model predictions with both stationary and rotating cascade results will be reported in the dissertation. A stationary cascade including five double-circular-arc profile blades has been constructed and is in operation. Initial results compare favorably with predictions of the analysis, and it is felt that treatment of the end-wall boundary layer will prevent unloading of the cascade at high incidence angles and provide better agreement. It is planned to complete the initial evaluation of the prediction technique by comparing results with losses and turning angles as measured behind the first stage rotor of the high-speed research compressor.

Instrumentation for these tests was acquired and installed in preparation for the planned experiments. A 5-hole yaw probe was mounted in an automatic traverse so that exit flow angles and pressures behind the rotor can be determined. A total temperature probe has been installed behind the first stage rotor, as have two miniature high-response KULITE probes for studies of stalling behavior. Inlet probes will measure the mass flow of air into the compressor.

A discharge plenum has been designed and installed on the high-speed research compressor. In initial tests, this plenum will provide for operation at selected points on the characteristic of the three-stage compressor. Following completion of these tests and the measurement of exit flow angles and losses associated with the first stage, it is planned to investigate the unsteady stalling behavior of both the compression system and the first stage, employing primarily the high response probes.

Preparations were made for a series of experiments in the low-speed compressor which will involve high-response pressure measurements on and behind the rotor blades. A six-channel data coupling system using FM telemetry was completed and is being installed on the rotor. This system will transmit the output of six KULITE transducers mounted at the 85% span position on the suction side of a rotor blade. Experiments planned include the completion of a study of rotating stall in the machine,

and the beginning of a new series of experiments designed to study the time response of the rotor blades to stall-producing disturbances.

References

1. Moses, H. L., Jones, R. R., O'Brien, W. F., and R. S. Peterson, "Simultaneous Solution of the Boundary Layer and Freestream with Separated Flow", AIAA J., Vol. 16, No. 1, January 1978, pp. 61-66.

Semi-Annual Progress Report

EFFECTS OF TURBULENCE ON FLOW THROUGH AN AXIAL COMPRESSOR BLADE CASCADE

Colorado State University, Fort Collins, Colorado 80523
Subcontract No. 8960-15

Professor Willy Z. Sadeh, Principal Investigator

Introduction

The long-term objective of this research program is the determination of the effect of oncoming turbulence in reducing the aerodynamic losses in flow through a blade cascade of an axial-flow compressor at blade-chord Reynolds numbers ranging from $2x10^5$ to $5x10^4$. Within this Reynolds-number range the laminar separation of the boundary layer along the profile suction surface leads to prohibitively high aerodynamic losses and even to fully stalled blades. Significant diminution of the separation losses is achievable by arresting the growth of the laminar separation bubble and, furthermore, by preventing its very occurrence. These goals can be accomplished by fostering the development of a turbulent boundary layer on the profile suction side. Realization of such a boundary layer depends upon supplying oncoming turbulence of sufficient energy at scales commensurate with the thickness of the prevailing profile boundary layer. Accumulation of turbulent energy at desired scales is produced through the selective amplification of outer turbulence. This organized turbulence amplification is governed by the stretching and accompanying streamwise biased tilting of cross-vortex tubes characteristic to forward stagnation flow. This research program is divided into three distinct phases addressed to methodically investigating the evolution of oncoming turbulence, its selective amplification at particular scales and the effect of the amplified turbulence on the boundary layer in flow: (1) about a circular cylinder-the first phase; (2) about several selected single airfoils-the second phase; and, (3) through a stationary blade cascade-the third phase. The first phase represents a diagnostic study conceived for supplying the basic guidelines for efficiently conducting the investigations of the other two subsequent phases.

Discussion

The research efforts are currently addressed to meeting the objectives of the first phase. An extensive visualization study of the turbulent flow near the stagnation zone of a circular cylinder and of the interaction of the amplified turbulence with the cylinder boundary layer was completed. The findings of this visualization study are presented in a Project SQUID technical report [1]. A summary motion picture that highlights the most instructive views was produced.

The effect of the amplified turbulence upon the position of the separation line on a circular cylinder at subcritical cylinder-diameter Reynolds numbers ranging from $5x10^4$ to $2x10^5$ is presently being investigated. In the absence of turbulence in the stream or surface roughness, the boundary layer is laminar until its separation up to a Reynolds number of about $2x10^5$. Then the laminar separation angle, measured from the forward stagnation point, is about 80° within this subcritical Reynolds-number range. The surface of the cylinder used is extremely smooth since its relative surface roughness is of the order of $5x10^{-5}$. A surface film coating technique was utilized for visualizing the position of the separation line for both laminar and turbulent approaching flows. Turbulence was superimposed by means of a turbulence-generating grid that was specifically conceived to produce turbulence susceptible to undergoing amplification at selected scales through the stretching mechanism. An illustration of how the amplified streamwise turbulence affects the location of the separation line on a circular cylinder at a Reynolds number of $9x10^4$ is provided by the still photograph given in Fig. 1. Both the observed laminar and turbulent separation lines are shown in this figure. A downstream shifting Δs along the cylinder circumference of approximately 5.5 cm (2.2 in) was effected by the oncoming amplified turbulence. The corresponding increase in the separation angle was about 40°. This shift was obtained with the grid installed at an upwind fetch of 7 cylinder diameters. The wake was simultaneously visualized for estimating the effect of the amplified turbulence upon its gross structure. By and large, the wake became narrower and the eddies were observed closer to the cylinder.

Measurements of the cylinder boundary-layer characteristics are currently being completed at five Reynolds numbers within the range $2x10^5$ to $5x10^4$ for both laminar and turbulent flow conditions. Based on the wall pressure distribution for both oncoming laminar and turbulent flows, the separation angle was estimated. In the case of laminar flow (no upwind turbulence-generating grid), a separation angle of about 80° was found at all Reynolds numbers. When the turbulence was superimposed by means of the grid, significant downstream shifts in the separation angle up to a certain maximum were detected with increasing Reynolds numbers for each upwind grid position. Increases in the separation angle amounting from 15 to 45° were obtained depending upon the particular combination of the Reynolds number and the grid upwind

distance. The variation of the increase in the separation angle $\Delta\theta_s$ with augmenting Reynolds numbers from 5×10^4 to 2×10^5 for three particular grid positions-viz., x_{2g} = 4, 7 and 10 diameters upwind-is portrayed in Fig. 2. Concurrently with the retardation of the separation, a drastic diminution of the drag coefficient was found. A decrease in the turbulent drag coefficient up to 40% of its laminar counterpart was obtained as the Reynolds number reached 2×10^5. These results clearly indicate that controlled superposition of adequate oncoming turbulence leads to its selective amplification and, ultimately, to its interaction with the body boundary layer. This interaction renders the boundary layer turbulent, retards the separation and, consequently, promotes reduction in the drag coefficient despite the prevailing subcritical Reynolds numbers. The separation angles and drag coefficients obtained are of the same magnitude as those characteristic of much higher supercritical Reynolds numbers.

The reduction and analysis of the data amassed during the surveys of turbulence characteristics and evolution in flow about a circular cylinder is being pursued. Measurements were performed at 21 stations at six different subcritical Reynolds numbers ranging from 5×10^4 to 2×10^5 and with the turbulence-generating grid installed at 4, 7 and 10 diameters upwind of the cylinder. Thus, data were collected at 378 stations. Preliminary results clearly indicate that the turbulent energy undergoes manifold amplification at scales larger than the neutral scales close to the body. A technical report describing the results of this survey is being prepared.

The examination of the matching of the inner and outer models of the vorticity-amplification theory have further been conducted. Several numerical schemes are presently being evaluated for carrying out the matching by means of a composite asymptotic expansion. The critical evaluation of the rapid-distortion and vorticity-amplification theories is being conducted. This effort is focused on determining the significance of the viscous dissipation and the relationship between the neutral scale and the integral scale of turbulence.

References

1. Sadeh, W. Z., Brauer, H. J. and Garrison, J. A., "Visualization Study of Vorticity Amplification in Stagnation Flow," Project SQUID TR CSU-1-PU, October 1977.

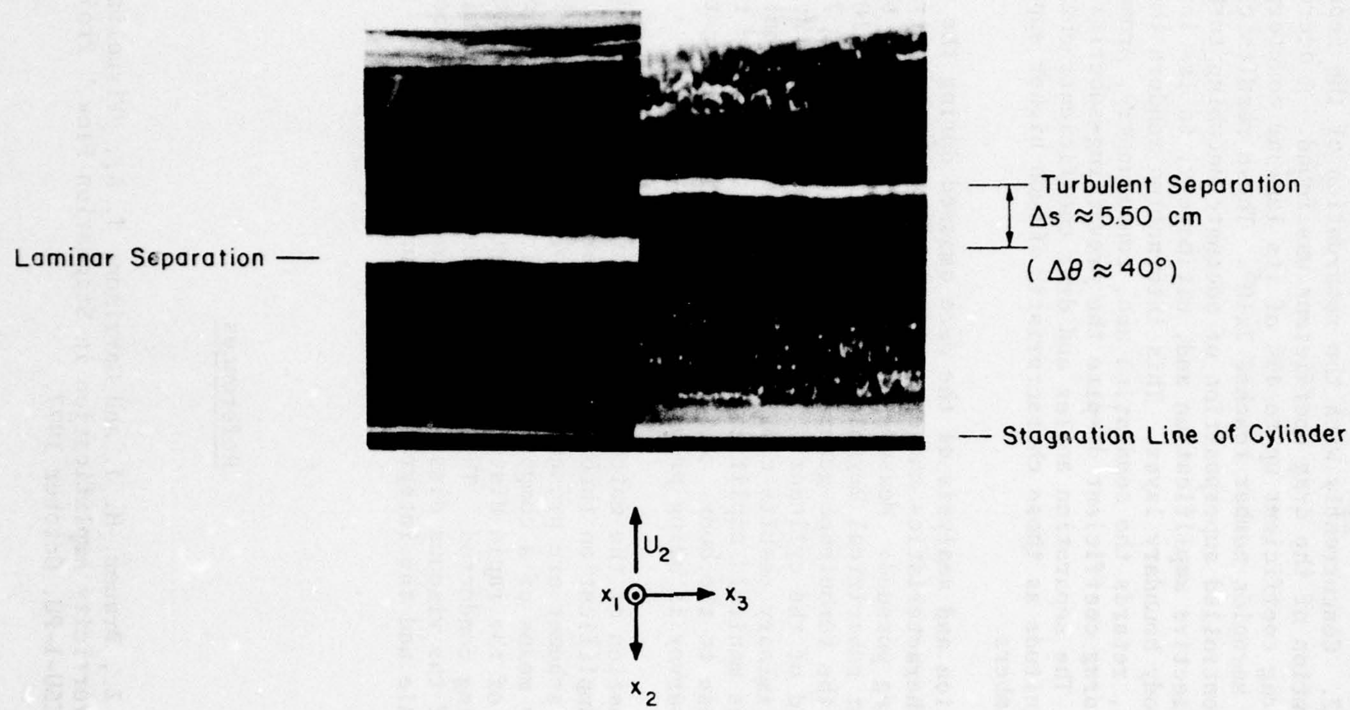


Fig. 1. Downstream shifting of the separation line along the circumference of a circular cylinder at a cylinder-diameter Reynolds number of 9×10^4 when turbulence is superimposed at 7 diameters upwind of the cylinder.

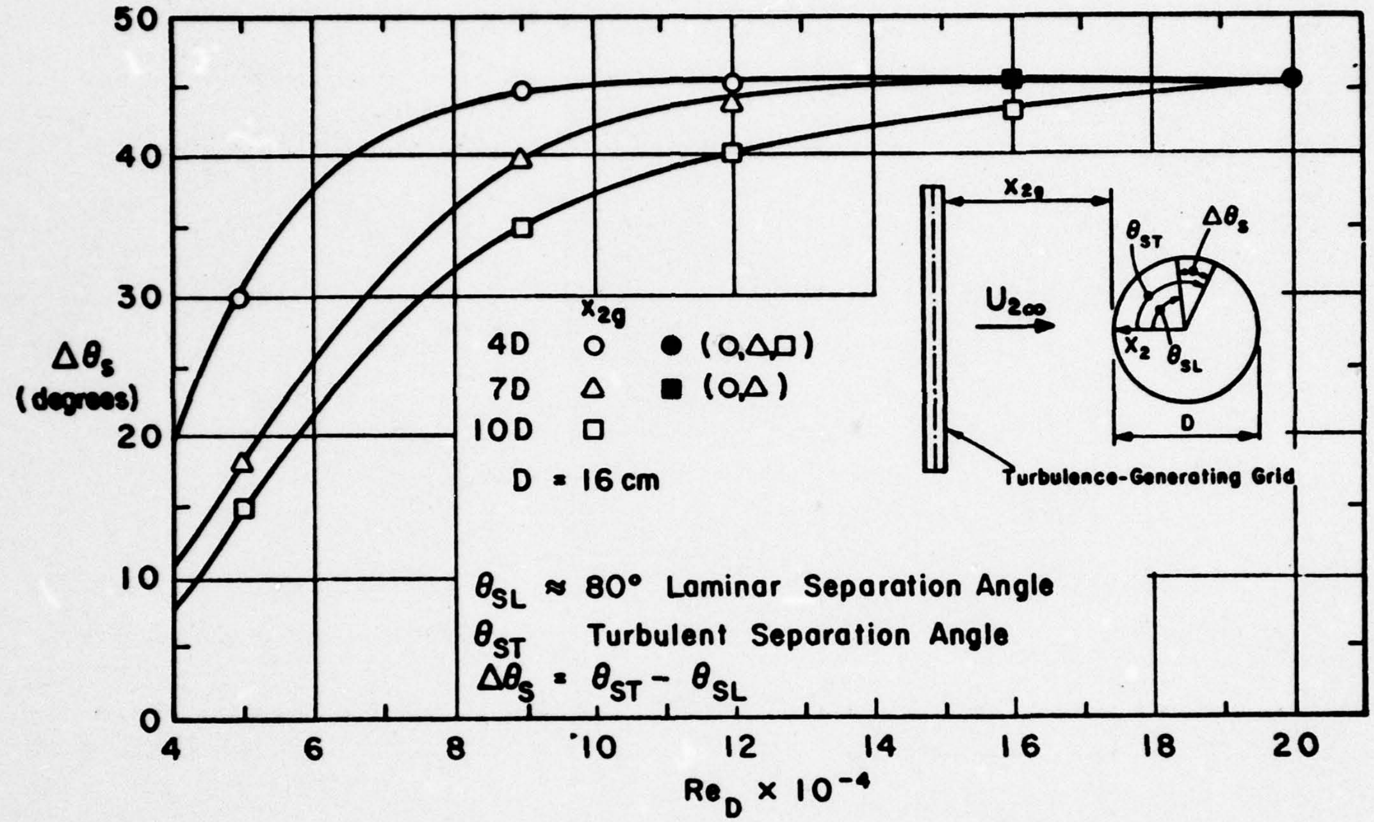


Fig. 2. Increase in the separation angle $\Delta\theta_S$ at subcritical Reynolds numbers induced by the interaction of the amplified turbulence with the cylinder boundary layer.

FUNDAMENTAL RESEARCH ON ADVERSE PRESSURE GRADIENT INDUCED TURBULENT BOUNDARY LAYER SEPARATION

Southern Methodist University, Dallas, Texas
Subcontract No. 8960-25

Professor Roger L. Simpson, Principal Investigator
Mr. G. P. Kokolis, Research Assistant

Introduction

The problem of turbulent boundary layer separation due to an adverse pressure gradient is an important factor in the design of many devices such as jet engines, rocket nozzles, airfoils and helicopter blades, and the design of fluidic logic systems. Until the last three years little quantitative experimental information was available on the flow structure downstream of separation because of the lack of proper instrumentation.

In 1974 after several years of development, a one velocity component directionally-sensitive laser anemometer system was used to reveal some new features of a separating turbulent boundary layer [1]. The directional sensitivity of the laser anemometer system was necessary since the magnitude and direction of the flow must be known when the flow moves in different directions at different instants in time [2]. In addition to much turbulence structure information, it was determined (1) that the law-of-the-wall velocity profile is apparently valid up to the beginning of intermittent separation; (2) that the location of the beginning of intermittent separation or the upstreammost location where separation occurs intermittently is located close to where the free-stream pressure gradient begins to rapidly decrease; (3) that the normal stress terms of the momentum and turbulence kinetic energy equations are important near separation; and (4) that the separated flowfield shows some similiarity of the streamwise velocity U, of the velocity fluctuation u', and of the fraction of time that the flow moves downstream [3].

Based upon these results, modifications [4,5] to the Bradshaw, et al. [6] boundary layer prediction method were made with significant improvements. However, this prediction effort pointed to the need to understand the relationship between the pressure gradient relaxation and the intermittent separation region structure. Another limiting factor for further refinement of the prediction of separated flows is the lack of fundamental velocity and turbulence structure information, especially in the backflow region. Thus, the objective of the current research program is to provide this information by using a directionally-sensitive laser anemo-

meter system to determine quantitatively the turbulence structure of a separating and separated turbulent boundary layer.

Discussion

This current research program was begun October 1, 1976, to obtain laser anemometer measurements of the separating flow of another adverse pressure gradient turbulent boundary layer for an airfoil or cascade blade type pressure distribution. Considerable effort has been made to avoid mean flow three-dimensionality and measurements indicate that it is minimal.

Although it is a rather minor part of this research, a number of velocity profiles have been measured upstream of separation with a hot-wire anemometer. The streamwise skin-friction behavior is well described by the Ludwieg-Tillmann relation. The mean and streamwise fluctuation velocity profiles agree with previously published results. Crossed hot-wire measurements of $\overline{u^2}$, $-\overline{uv}$, and $\overline{v^2}$ as well as $\overline{u^2v}$ and $\overline{v^2}$ are currently being made in regions without backflow. The latter two quantities are necessary for determining the large eddy diffusion of turbulence energy. The spectra of $\overline{u^2}$ and $\overline{v^2}$ are being examined to determine the characteristic frequencies of the large-eddy structures.

Many measurements of U, V, $\overline{u^2}$, $\overline{v^2}$, $(U-V)/\sqrt{2}$, $-\overline{uv}$, the flow reversal intermittency, the skewness, and flatness of the velocity probability distributions, and velocity spectra are being obtained with the laser anemometer system in the vicinity of separation.

Figure 1 show some of these results [6]. A logarithmic mean velocity profile region near the wall persists well downstream of the beginning of intermittent backflow at the 127 inches location. As observed in the earlier research the mean velocity U profile is flat near the wall at the streamwise location (135 inches) where the mean wall shearing stress is zero. Downstream the backflow region appears to be divided into three layers: a viscous layer nearest the wall that is dominated by the flow unsteadiness, a rather flat intermediate layer that seems to act as an overlap region between the viscous wall and outer regions, and the outer flow region that is really part of the large-scaled downstream flow. The Reynolds shearing stresses are large in the outer region and approach zero in the viscous layer. Analysis of these data is not yet complete.

It is clear from Figure 2 that the $\sqrt{\overline{u^2}}$ and $\sqrt{\overline{v^2}}$ fluctuations are comparable to the mean velocity in the separation region near the wall. Since the freestream velocity in the separation region is observed to be rather steady, this means that the near wall fluctuations are not mainly due to a flapping of the entire shear layer, but due to turbulence within the separated shear layer.

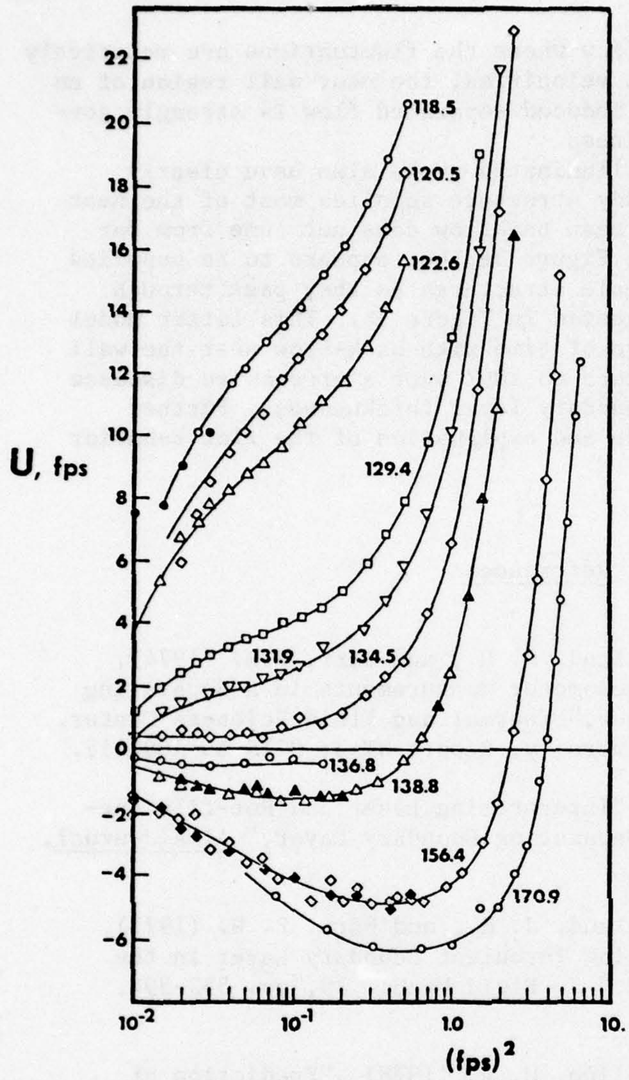


Figure 1. Mean velocity profiles at several streamwise locations for steady free-stream separating flow. Solid lines for visual aid only.

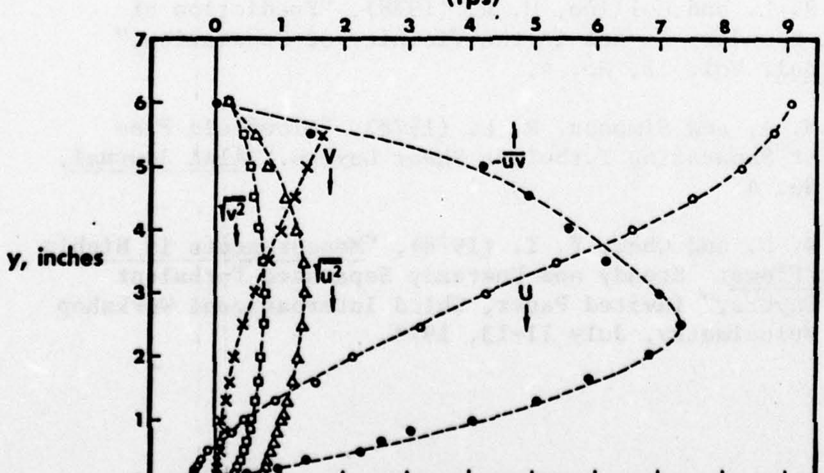


Figure 2. Mean and fluctuation velocity profiles for the 138.8 inches location. Dashed lines for visual aid only.

Thus, unlike an attached flow where the fluctuations are relatively small compared to the mean velocities, the near wall region of an adverse pressure gradient induced separated flow is strongly governed by the flow unsteadiness.

Ciné films of laser-illuminated smoke also have clearly revealed that the large eddy structure supplies most of the near wall backflow. The small mean backflow does not come from far downstream as suggested in Figure 3a, but appears to be supplied intermittently by large-scale structures as they pass through the separated flow as suggested in Figure 3b. This latter model explains why the percentage of time with back-flow near the wall varies continuously from zero to 100% over a streamwise distance of more than 10 initial boundary layer thicknesses. Further measurements are being made and explanation of the flow behavior is being pursued.

References

1. Simpson, R. L., Strickland, J. H., and Barr, P.W. (1974), "Laser and Hot-film Anemometer Measurements in a Separating Turbulent Boundary Layer," Thermal and Fluid Sciences Center, Southern Methodist University, Report WT-3; NTIS AD-A001115.

2. Simpson, R.L. (1976), "Interpreting Laser and Hot-film Anemometer Signals in a Separating Boundary Layer," AIAA Journal, 14, pp. 124-126.

3. Simpson, R. L., Strickland, J. H., and Barr, P. W. (1977), "Features of a Separating Turbulent Boundary Layer in the Vicinity of Separation," J. Fluid Mech., 79, pp. 553-594, 9 March.

4. Simpson, R. L. and Collins, M. A. (1978), "Prediction of Turbulent Boundary Layers in the Vicinity of Separation," AIAA Journal, Vol. 16, No. 4.

5. Collins, M. A. and Simpson, R. L. (1978), "Flowfield Prediction for Separating Turbulent Shear Layers," AIAA Journal, Vol. 16, No. 4.

6. Simpson, R. L. and Chew, Y. T. (1978), "Measurements in Highly Turbulent Flows: Steady and Unsteady Separated Turbulent Boundary Layers," Invited Paper, Third International Workshop on Laser Velocimetry, July 11-13, 1978.

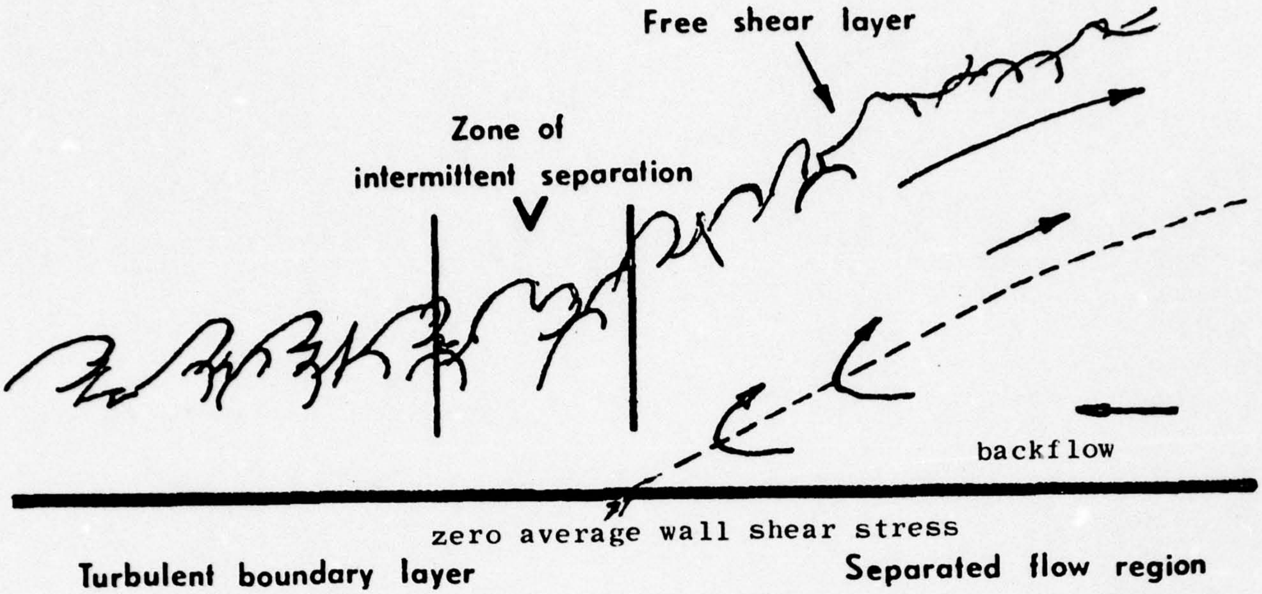


Figure 3 a. Traditional view of turbulent boundary layer separation with the mean backflow coming from far downstream.

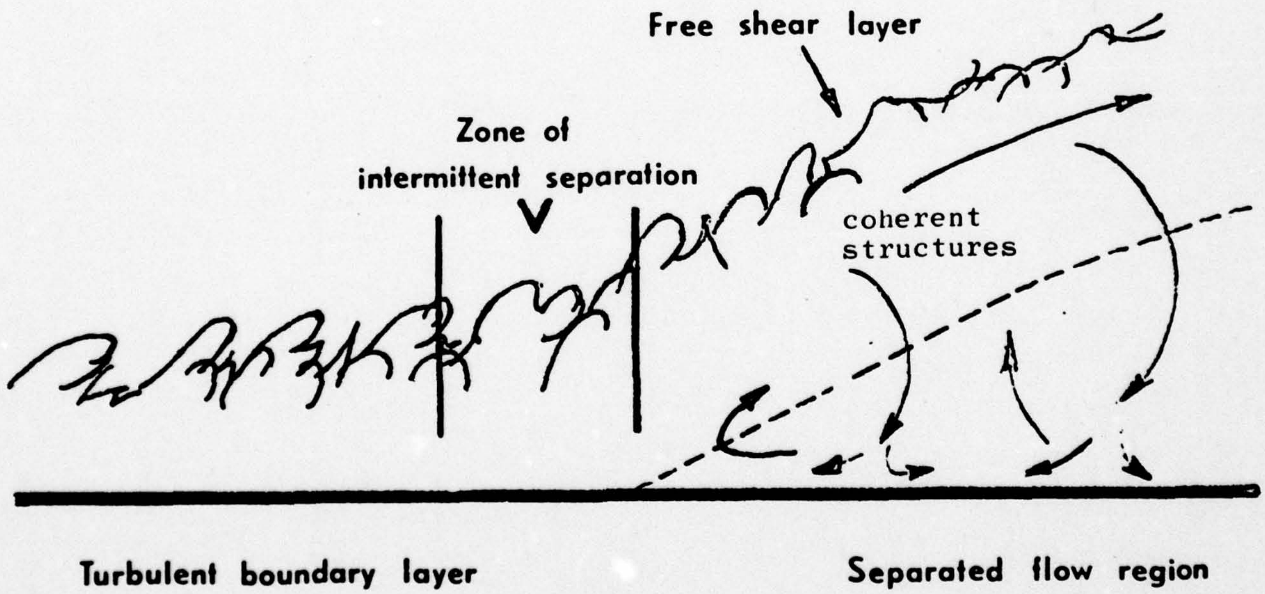


Figure 3b. A possible flow model with the coherent structures supplying the small mean backflow.

II. COMBUSTION AND CHEMICAL KINETICS

October 1978

PREPARATION OF MANUSCRIPT ON IONIZATION IN FLAMES

AeroChem Research Laboratories, Inc., Princeton, NJ 08540
Subcontract No. 8960-32

Hartwell F. Calcote, Principal Investigator

Introduction

The purpose of this program, initiated 1 September 1978, is to bring together in a critical way the extensive literature which has developed over the years on ionization in flames. This literature includes not only fundamental studies of the mechanism of ionization in flames but the application of flame ionization to such practical problems as radar attenuation in rocket exhausts, flame ionization detectors for gas chromatography, MHD power generation, and flame and smoke detection.

Discussion

The literature is being organized and some comparative analysis of the results of various investigators has been initiated. The immediate objective is to weed out real from imagined observations and dreamed up from supported conclusions.

A SHOCK TUBE STUDY OF H_2 AND CH_4 OXIDATION WITH N_2O AS OXIDANT

University of Missouri, Columbia, Missouri
Subcontract No. 8960-21

Prof. Anthony M. Dean, Principal Investigator

Introduction

The study of oxidation reactions in shock tubes has been stimulated by the use of fast, accurate numerical integration routines. Now it is possible for kineticists to more definitively test various oxidation mechanisms by a detailed comparison of calculated and observed concentration-time profiles. Although the $H_2/O_2/Ar$ and $H_2/O_2/CO/Ar$ systems have been successfully studied by this approach, extension to even simple hydrocarbon systems like CH_4/O_2 has been limited by lack of reliable high temperature rate constants. A common practice has been to extrapolate low temperature flow system data to the temperature range of interest. Unfortunately this approach can lead to serious errors; recent studies have convincingly demonstrated that many reactions of importance in combustion mechanisms exhibit markedly "non-Arrhenius" rate constants. In this light it appears to be most desirable to measure rate constants in the same high temperature regime where they will be used to test the combustion mechanisms. However, it is equally important that these data be obtained from relatively simple systems where assignment of the desired rate constant is not contingent upon proper assignment of a complex mechanism and the associated rate constants.

The basis of our SQUID work is the substitution of N_2O for O_2 in combustion studies. Earlier work in our laboratory [1] suggested that the high temperature dissociation of N_2O might serve as a useful source of oxygen atoms. Use of N_2O as the oxidizer in combustion studies would then allow one to study the rate of the reaction between oxygen atoms and the fuel. The main advantage of the substitution is that the kinetics are simpler; here one need not consider reactions of oxygen molecules as in a normal combustion system. Our initial efforts in the SQUID program concentrated on further refinement of the N_2O dissociation kinetics and measurement of the recombination rate of oxygen atoms and carbon monoxide [2]. The substitution technique was then tested on a series of experiments with hydrogen as the fuel [3]. Here it was possible to compare the rate constant for the reaction $O + H_2 \longrightarrow OH + H$ obtained via our $N_2O/H_2/CO/Ar$ work with that obtained from the traditional studies of $H_2/O_2/Ar$ system. Good agreement was obtained; it was also possible in this work to obtain high temperature rate constants for $OH + CO \longrightarrow CO_2 + H$ and $H + N_2O \longrightarrow N_2 + OH$.

With the validity of the technique established, our attention then focused upon study of the methane system. Here there is appreciable uncertainity in rate constant assignments for important reactions. Analysis of our data at high temperature ($2400<T<3000$ K) yielded values for the rate constant of the reaction $O + CH_4 \longrightarrow CH_3 + OH$ much higher than one would obtain from the usual extrapolations of the low temperature data. This value was in good agreement with a very recent high temperature measurement. These results reinforced the thesis that rate constants used in modeling calculations should come from high temperature measurements. Analysis of the methane data at lower temperatures ($1800<T<2200$ K) suggested unsuspected complexities in the mechanism. Subsequent experiments strongly suggested that reactions of formaldehyde (CH_2O) were responsible. As a result of this observation, our attention shifted to a detailed study of these reactions. Our initial efforts were aimed at the simpler CH_2O/Ar systems. With these results in hand, it would be easier to understand the $CH_2O/N_2O/Ar$ system.

Discussion

The CH_2O/Ar work has been completed [4]. Here CH_2O decay was followed in 0.1%, 0.5% and 1.0% mixtures. The data were interpreted in terms of the following mechanism:

$$CH_2O + M \longrightarrow HCO + H + M \qquad (1)$$

$$CH_2O + H \longrightarrow HCO + H_2 \qquad (2)$$

$$HCO + M \longrightarrow H + CO + M \qquad (3)$$

$$HCO + H \longrightarrow H_2 + CO \qquad (4)$$

The results were shown to be quantitatively consistent with this mechanism and rate constants were assigned. Although it was clear that k_1 must be significantly smaller than previously reported [5], it was not possible to unequivocally assign a value here. Instead there were a series of combinations of k_1 and k_2 which fit the data.

In an attempt to cast more light upon the proper k_1, k_2 combination, measurements of CH_2O decay, CO_2 production, and oxygen atom production were performed with $CH_2O/O_2/Ar$ and $CH_2O/O2/CO/Ar$ mixtures. Analysis of this data strongly suggests that one particular combination of k_1 and k_2 is superior in explaining these observations. In addition to the information on k_1 and k_2, these experiments, in conjunction with others on $CH_2O/N_2O/Ar$ and $CH_2O/N_2O/CO/Ar$ systems, allowed us to obtain good estimates for high temperature rate constants for two other important formaldehyde reactions:

$$OH + CH_2O \longrightarrow HCO + H_2O \qquad (5)$$

$$O + CH_2O \longrightarrow HCO + OH \qquad (6)$$

These rate constants assignments are now being checked by detailed analysis of the lower temperature methane data discussed earlier. Preliminary results indicate that much better agreement is now obtained in that system.

The digression into formaldehyde chemistry has been unexpectedly fruitful. It would appear that our new values for rate constants of the reactions listed above will now allow us to properly characterize the N_2O/CH_4 system and more realiably assign a high temperature rate constant to the reaction $O + CH_4 \longrightarrow CH_3 + OH$. In addition, the formaldehyde rate constants obtained should be appreciably more reliable than those presently used in computer modeling studies. These values are quite important since formaldehyde is an important intermediate in a host of combustion systems.

Notes and References

1. S. C. Baber and A. M. Dean, Int. J. Chem. Kinet., 7, 381 (1975).

2. A. M. Dean and D. C. Steiner, J. Chem. Phys., 76, 598 (1977). (Project SQUID Technical Report UMO-1-PU.)

3. A. M. Dean, D. C. Steiner, and E. E. Wang, Comb. and Flame, 32, 73 (1978). (Project SQUID Technical Report UMO-2-PU.)

4. A. M. Dean, B. L. Craig, R. L. Johnson, M. C. Schultz and E. E. Wang, Project SQUID Technical Report UMO-3-PU. (To be published in the Seventeenth International Symposium on Combustion volume.)

5. H. G. Schecker and W. Jost, Ber. Bunsenges Physik Chem., 73, 521 (1969).

COMBUSTION KINETICS AND REACTIVE SCATTERING EXPERIMENTS

Yale University, New Haven, Connecticut
Subcontract No. 4965-16

J. B. Fenn, Principal Investigator
R. J. Gallagher and C.G.M. Quah

Introduction

The combustion of hydrocarbon fuels has been man's most used source of useful energy for much of this century. The chemical reactions which it involves have been among the most studied. And yet, there remains uncertainty as to the nature of the first reactive step in the complex sequence of reactions by which oxygen and hydrocarbon molecules become hot combustion products. This investigation comprises an attempt to identify that first reactive event and to determine its cross section by means of molecular beam scattering methods. The prospective advantage of such methods is that they can examine the consequences of a single collision between individual molecules. By the same token they are substantially limited in their ability to probe intermediate reaction steps which involve species of transient existence such as free radicals not readily obtainable as beams.

Discussion

In the last report we had confessed our lack of success in obtaining any observable reaction between oxygen molecules and butane molecules under the single collision conditions of our experiment. We then suggested that we would try replacing oxygen by a more reactive molecule, e.g., chlorine. In further consideration of this possibility and in view of the fact that our program was in the twilight of its sponsorship we decided instead to devote the remaining resources to some efforts which promised more certain return. Accordingly, we finished up some loose ends of work on energy exchange which had been almost completed in earlier phases of our SQUID sponsorship.

In one of these clean-up details we examined experimental results we had obtained on relaxation of internal energy in methane and its chlorinated derivatives, CH_nCl_{4-n} where n ranged from one to four. It will be recalled that the approach consists in determining, by velocity analysis of a molecular beam extracted from a freely expanding supersonic jet, the total amount of translational energy in the beam molecules, both thermal and convective. An energy balance based on the source gas temperature identifies the amount of residual energy remaining in internal degrees of freedom. From the dependence of this residual energy upon source Reynolds number

we are able in principle to determine the characteristic relaxation rate. In the case of CH_4 it turns out that none of the vibrational energy relaxes during expansion. Consequently, it was possible to determine the rotational relaxation rate. In terms of so-called rotational collision number Z_r we found a value of 15 at a source temperature of 314 K which is in good agreement with the value 14-17 obtained by Kelley with ultrasonic dispersion techniques.(1) At a source temperature of 900 K a somewhat higher value of 20 provided the best fit to the data. There are no previous data at this temperature to which we can compare our results.

In the case of the chlorinated derivatives at least some of the vibrational energy relaxed during the expansion. Consequently, it was not feasible to infer a characteristic relaxation rate for either rotation or vibration from the energy balance alone. We would need independent information on one or the other of these degrees of freedom in order to arrive at unequivocal results. However, it did emerge quite clearly that in the case of molecules containing more than one Cl there were at least two characteristic vibrational relaxation rates in each case, presumably resulting from substantial differences in TV exchange cross sections for different vibrational modes. Such differences had emerged in ultra sound measurements on CH_2Cl_2 and had been predicted for $CHCl_3$ and CCl_4 but not previously observed.(2,3) These results were presented in a paper at the XIth International Symposium on Rarefied Gas Dynamics in July.(4)

Pursuing another aspect of intermolecular energy exchange we have analyzed the differences between two methods of obtaining relaxation rates from free jet expansion measurements. In one, which was originally developed under SQUID sponsorship in our laboratory and used in determining Z_r for CH_4 in the study already mentioned, the relaxation rate equation is integrated numerically over the range of conditions in the free jet from the source to the end of the expansion with relaxation collision number Z as a parameter.(5) The appropriate value of Z is determined by matching experimental and calculated results. Another approach which has been widely used invokes the so-called "sudden freeze model". It assumes that equilibrium is maintained in the jet until the density decreases to a critical value. At that point the relaxation process abruptly stops and the relaxing mode is frozen during the rest of the expansion. At the freezing point, which is identified with the experimental value of the terminal internal temperature, the kinetically possible relaxation rate is presumed to be just equal to the rate which is required by and known from gas dynamic considerations to maintain equilibrium at that point in the jet. Results from the sudden freeze model and numerical integration have not been previously compared. We carried out integrations over a wide range of source conditions, characteristic rates and specific heat ratios. From the results we were able to arrive at a simple correction to the sudden freeze model which makes it agree closely with the presumably more accurate numerical integration. In addition, our

findings make possible a fairly accurate and rapid estimation of characteristic rate from a single experimental observation of terminal internal temperature. The results should apply to any mode of relaxation for which a terminal temperature can be identified and which is described by the usual relaxation rate equation. This study, in which Professor D. R. Miller of UCSD collaborated, also formed the basis for a paper presented at the XIth International Symposium on Rarefied Gas Dynamics.(6)

References

1. B. T. Kelley, J. Acoust. Soc. Amer. 29, 1005 (1957).

2. T. L. Cottrell and J. C. McCoubrey,"Molecular Energy Transfer in Gases,"Butterworths, London, 1961.

3. F. Tanczos, J. Chem. Phys. 25, 439 (1956).

4. R. J. Gallagher and J. B. Fenn, "Internal Energy Relaxation in Methane and Its Chlorinated Derivatives," presented at the XIth International Symposium on Rarefied Gas Dynamics, Cannes, France, July 1978.

5. R. J. Gallagher and J. B. Fenn, J. Chem. Phys. 60, 3487 (1974).

6. C.G.M. Quah, J. B. Fenn and D. R. Miller, "Internal Energy Relaxation Rates from Observations on Free Jets," presented at the XIth International Symposium on Rarefied Gas Dynamics, Cannes, France, July 1978.

HIGH-TEMPERATURE FAST-FLOW REACTOR CHEMICAL KINETICS STUDIES

AeroChem Research Laboratories, Inc., Princeton, NJ 08540
Subcontract 8960-16

Arthur Fontijn, Principal Investigator

Introduction

Reliable quantitative knowledge of the kinetics of free metal atom and metal oxide species is required for a better understanding and description of (i) the burning of metallized propellants and (ii) the exhaust properties of rockets using such propellants. Suitable techniques for obtaining such kinetic information were unavailable until we adapted the tubular fast-flow reactor technique to reach temperatures up to 2000 K (1). This development has extended an essentially room temperature technique to being capable of being used for making measurements in the temperature range of conventional high-temperature techniques such as flames and shock tubes.

The agreement between (extrapolated) rate coefficients obtained from high and low temperature determinations by separate techniques is often poor. It is also becoming apparent that, for many reactions, Arrhenius-type plots of rate coefficients vs. T covering ranges on the order of 1000 K or more show distinct upward curvature with increasing T (e.g. Refs. 2-4), thus making extrapolation of k(T) data over wide temperature ranges a procedure of doubtful validity. For reliable k(T) measurements it is desirable to use a single technique to span the entire T-range of interest. For the 300-2000 K range our high-temperature fast-flow reactor (HTFFR) technique provides such a technique for the first time.

Discussion

Experiments are performed on the reaction

$$Al + SO_2 \rightarrow AlO + SO \qquad [1]$$

The reasons for studying this reaction and the status of this work have been discussed in the semi-annual report of April 1977, at which time work was interrupted for lack of funding. Funding for the October 1977 - February 1979 SQUID year, which should allow completion of the study of Reaction [1], was received by mid-July 1978. The apparatus has been readied for a resumption of the work. There are no new results to report as yet.

References

1. Fontijn, A., Kurzius, S.C., Houghton, J.J., and Emerson, J.A., "Tubular Fast-Flow Reactor for High-Temperature Gas Kinetic Studies," Rev. Sci. Instr. 43, 726 (1972).

2. Westenberg, A.A. and deHaas, N., "Rates of $CO + OH$ and $H_2 + OH$ Over an Extended Temperature Range, " J. Chem. Phys. 58, 4061 (1973).

3. Rawlins, W.T. and Gardiner, W.C., "Rate Constants of $OH + OH \rightarrow H_2O + O$ from 1500 to 2000 K," J. Chem. Phys. 60, 4676 (1974).

4. Fontijn, A. and Felder, W., "HTFFR Kinetics Studies of $Al + CO_2 \rightarrow AlO + CO$ from 300 to 1900 K, A Non-Arrhenius Reaction," AeroChem TP-353, March 1977, Project SQUID AC-16-PU, J. Chem. Phys. 67, 1561 (1977).

ISOTOPIC STUDIES OF THE CHEMICAL MECHANISMS OF SOOT NUCLEATION

Kansas State University, Manhattan, Kansas
Subcontract No. 8960-33

Dr. T. W. Lester, Principal Investigator
Dr. J. F. Merklin, Co-Principal Investigator
Mr. S. N. Vaughn, Research Assistant
Mr. J. K. Garrett, Research Assistant

Introduction

The purpose of this research is to determine experimentally the principal chemical mechanisms of soot nucleation at temperatures and pressures comparable to those found in gas turbine combustors. Of specific interest will be the extent of conversion of heteratomic species, typical of synthetic fuels, to soot. Initial tests will be conducted using laser extinction measurements to ascertain the extent of conversion and gas chromatographic and mass spectrometric techniques to monitor the progress of the chemical reactions. Initially, it will be determined whether the soot nucleation is due primarily to ring condensation or fragmentation.

Discussion

"Soot" refers generally to the various dispersed particles ranging in size from a few molecular diameters to microns which accompany hydrocarbon combustion. Its chemical composition varies, but most generally soot is about 99 percent solid carbon and 1 percent hydrogen by weight. The phenomenon of soot formation from combustion processes, and particularly from flames, has been studied for many years. Since the early Nineteenth Century, attempts have been made to provide a viable mechanism of soot formation. More recently, the production of soot from hydrocarbon combustion has become of considerable importance from both a pollutant and a performance point of view. The problems have been well documented.

The concern about carbon formation is well founded. The increased levels of radiation are especially deleterious in combustors used in aircraft because the weight limitation requires that these burners be designed somewhat marginally. Moreover, sooting fouls turbine blades. When synthetic fuels are introduced in the future, to augment or replace petroleum fuels, the soot formation problem will certainly worsen (1). The high aromatic content of synthetic fuels is responsible for this increased soot formation. While petroleum fuels have an aromatic content of 10 to 15 percent, coal-derived liquid fuels can exceed 50 percent, and shale oil, although closer to petroleum in aromatic content, may have 15 to 30 percent. Palmer and Cullis (2) have discussed how hydrogen/carbon ratio is a good measure of smoking tendency. Petroleum fuels have a high H/C ratio close to 2, coal liquids such as kerosine has a ratio around 1.25, and shale oil can be processed to have a ratio of up to 1.9. The smoking problem is so potentially troublesome that the Air Force is devoting considerable effort to bring the chemical and physical properties of synthetic fuels closer to those exhibited by petroleum (3).

A primary motivation for this research is a desire for a better understanding of the early stages in the formation of high molecular weight hydrocarbons from simpler ones. While global routes to soot formation have been identified and many hydrocarbons in the process catalogued, there is still a great deal of uncertainty about the important reactions. In this study the chemical mechanisms of soot nucleation from aromatic and heteroaromatic constituents of synthetic fuels will be studied with the use of model compounds and a single-pulse shock tube. Specifically of interest will be whether soot nucleation occurs via polymerization of the aromatic molecules or by condensation of smaller molecules, resulting from fragmentation of the parent hydrocarbons.

In recent years, numerous investigations have added considerable insight. Today the literature, as surveyed by Palmer and Cullis (2) and Gaydon and Wolfhard (4), is replete with soot formation studies. Howard (5) has recently contributed considerable experimental information, postulated a modified formation mechanism and provoked stimulating discussions and new interest in the field. Wersborg, et al. (6), have presented recent experimental findings which support, in most instances, Howard's hypothesis.

The majority of studies have been performed in flames, where temperature, concentration, and velocity gradients complicate determination of the formation mechanism. In exploring the nucleation of soot under temperatures and pressures comparable to gas turbine combustors, the shock tube has rather unique advantages. Its reflected shock region provides a reaction environment largely void of property gradients and sequential measurements may be performed on one sample of gas. The purpose of this investigation is to apply the advantages of the shock tube in conjunction with

mass spectrometric diagnostic techniques to better define the gas phase kinetics preceding the nucleation of soot. Heteroaromatic compounds such as thiophene (C_4H_4S) and pyridine (C_5H_5N) will be shock heated, quenched, sampled, analyzed by gas chromatography and mass spectrometry and be compared to results from benzene. The reaction temperatures and pressures will be varied from 1000 K to 2500 K, and 1 atm to 10 atm respectively. The reaction time will be varied from 100 μsec to 2 msec, and the oxygen-heteroaromatic fuel ratio will be varied from zero to fuel lean conditions.

The project was initiated on August 1, 1978; therefore, progress to date has been confined to requesting bids on a mass spectrometer, ordering a full port ball valve in order to complete modification of the existing single pulse shock tube, and designing a preliminary series of experiments. However, it is anticipated that during the six months ending February 28, 1979, the mass spectrometer system will have been installed and tested out. To test the efficacy of our experimental technique, a compound with known decomposition kinetics, will be used. Accordingly, the sensitivity of the rate constant will enable us to check the temperature of the reaction system to that predicted from ideal shock relations.

Notes and References

1. Longwell, J. P., "Synthetic Fuels and Combustion," Sixteenth Symposium (International) on Combustion, p. 1, The Combustion Institute, Pittsburgh, 1977.

2. Palmer, H. B. and Cullis, C. F. (1965), "The Formation of Carbon from Gases," in The Chemistry and Physics of Carbon, I, P. L. Walker, Jr., ed., Marcel Dekker, p. 265.

3. Blazowski, W. S., "Combustion Considerations for Future Jet Fuels," Sixteenth Symposium (International) on Combustion, p. 631, The Combustion Institute, Pittsburgh, 1977, and Blazowski, W. S., Fahrenbuick, F. S. and Tackett, L. P., "Combustion Characteristics of Oil Shale Derived Jet Fuels," Fall Meeting, Western States Section, The Combustion Institute, October 20, 1975, Paper 75-13. (Refer also to the AFOSR Contractor's Meeting on Combustion Dynamics, September 12, 1977, Purdue University).

4. Gaydon, A. G. and Wolfhard, H. G. (1970), Flames, Chapman and Hall, LTD., London, Chap. VIII.

5. Howard, J. B. (1969), Twelfth Symposium (International) on Combustion, The Combustion Institute, p. 877.

6. Wersborg, B. L., Yeung, A. C., and Howard, J. B., (1975), Fifteenth Symposium (International) on Combustion. The Combustion Institute, p. 1439.

PYROLYSIS OF SYNTHETIC FUELS USING THE LASER-POWERED HOMOGENEOUS PYROLYSIS TECHNIQUE

Cornell University, Ithaca, New York

Professor W. J. McLean, Principal Investigator
Ms. W. Lei, Research Assistant

Introduction

While a complete and detailed understanding of carbon particle formation and destruction in gas turbine combustors is not yet available, it is generally accepted that important luminosity and soot formation effects are intimately related to the rapid pyrolysis which occurs when these fuels are injected into the combustor (1,2,3). It is during this pyrolysis phase of the combustion that soot precursors, such as polyacetylenes and polyaromatic compounds, are formed. The objective of the present program is to experimentally investigate the pyrolysis of compounds characteristic of high carbon-to-hydrogen ratio synthetic fuels, with particular emphasis on the formation of soot precursors during these pyrolysis processes.

The pyrolysis studies are being carried out using the laser-powered homogeneous pyrolysis (LPHP) technique. This technique provides a method for homogeneously heating a gas sample by using small amounts of SF_6 or SiF_4, which have large absorption cross sections for a specific rotational line of a CO_2 laser. The fast vibration-translation relaxation time for the absorber then serves to rapidly heat the surrounding gas while the test cell walls remain near their initial temperature. Typically, the small quantities of the hydrocarbon reactant material in an argon diluent are heated rapidly to temperatures in the range 500 to 1800 K using irradiation times from fractions of a second up to several minutes. The pyrolysis products are rapidly cooled upon termination of the laser irradiation, and the progress of the decomposition reactions can be followed by analyzing the pyrolysis products by standard gas chromatographic and mass spectrometric techniques. Alternatively, time resolved pyrolysis reactions may be followed by continuous techniques such as resonance absorption or molecular beam mass spectrometry.

Discussion

Our current Project SQUID Program started in June 1978, and we are now completing analytical studies and initiating experiments. The analytical investigation of the temperature and velocity distributions in the laser-heated cells was undertaken prior to the SQUID program, and progress on that study is summarized here. In addition, we describe progress on the early stages of the experimental program.

The objective of the analytical study was to determine the temperature and flow distributions inside an LPHP cell. A numerical solution of the mass, momentum, and energy conservation equations was obtained. The numerical model included the nonlinear convection terms in the momentum and energy equations and also the transient behavior of the temperature and velocity fields. It allowed for a general form of the heat source term in the energy equation which varied both spatially and temporally, and, if necessary, with temperature and pressure.

The model was used to compute the temperature distribution in the LPHP cell over a wide range of conditions, including variations in absorbed power, cell pressure and laser irradiation profiles. These computations were for a cell of 1 cm diameter and 5 cm in height, similar to that used in previous experiments. More recently an improved model, which includes the effect of density variations on the heat source term, was used to analyze the 3 cm diameter 9 cm high cell being used in current experiments. Temperature transients within the cell were determined as were steady state temperature and velocity fields. The effect of cell pressure, cell size, and laser intensity were all investigated. In all cases, a relatively hot buoyant core is established in the center of the cell and a torroidal circulation cell moves cool fluid down the outside walls and back up through the central core. Since all heat losses are to the cool walls and because the heat source is more concentrated in the cell's center, a pronounced radial temperature gradient is present, with the temperature changing from 300 K at the wall to as high as 1400 K along the centerline. The axial velocity profiles indicate the expected buoyant convection flow patterns, where a strong buoyancy driven upward flow exists in a hot central core region, and the cooler regions along the outer walls exhibit downward flow. Radial velocities are almost zero except near the windows at the top and bottom where the convection currents move material from the central core to the outer region at the top and back towards the center at the bottom.

The first experiments are currently underway with the objective of measuring the temperature distribution in the sample cell with fine wire thermocouples. The effect of the direct radiation on the thermocouple will be evaluated, and experimental temperatures will be compared with analytical results. Upon completion of the temperature measurements, pyrolysis experiments will begin. Pyrolysis products from simple low molecular weight hydrocarbons will be determined and the results will be compared with available data from the literature. Pyrolysis of synthetic fuel components will then be studied with emphasis on formation of soot precursors from aromatic compounds. Both gas chromatography and mass spectrometry are to be employed for chemical analysis.

Notes and References

1. Longwell, J.P., "Synthetic Fuels and Combustion," Sixteenth Symposium (International) on Combustion, p. 1, The Combustion Institute, Pittsburgh, 1977.

2. Blazowski, W.S., "Combustion Considerations for Future Jet Fuels," Sixteenth Symposium (International) on Combustion, p. 1631, The Combustion Institute, Pittsburgh, 1977.

3. Wagner, H.G., "Soot Formation in Combustion, A Review," presented at Seventeenth Symposium (International) in Combustion, The University of Leeds, August 1978.

Semi-Annual Progress Report

FUNDAMENTAL STUDIES ON TURBULENT, SWIRLING JET IGNITION

Guggenheim Laboratories, Mechanical & Aerospace Engineering Dept.
Princeton University, Princeton, N.J. 08540
Subcontract Not Yet Awarded

Professor William A. Sirignano, Principal Investigator
Dr. Alon Gany, Research Staff Member
Mr. Stephen Parker, Ph.D. Candidate

Introduction

This study involves axisymmetric turbulent, swirling, combustion flows. The objective is to understand, via analysis and experimentation, the basic phenomena affecting the ignition, flame stabilization and combustion and to develop predictive techniques for actual combustor design. The study has been underway for a few months now (although the contract award has not been made yet.) The experimental and theoretical efforts are separately described in the following sections.

DISCUSSION

Experimental Study

An extensive study of various experimental concepts and apparatus designs for swirl generation is underway. We are considering both radial vanes and tangential injection as mechanisms for swirl generation in both the inner and outer flow ducts of our apparatus. Either mechanism would permit the achievement of the desired swirl numbers and flow conditions. With the first mechanism, the control on the various flow parameter will be via controlling four different flow rates, namely, the axial and tangential flow rates of both the inner and the outer streams. With the second mechanism, two flow rates plus orientations of two sets of vanes would be the control parameters. For fixed geometry and the same flow type (i.e., either cold or hot flows), the following parameters will be controllable with either mechanism:

(1) absolute axial fluid velocity and Reynolds number of both the inner and outer flows and the velocity ratio.
(2) the value and ratio of inner and outer flows swirl numbers within the range of design, when the axial velocities, velocity ratio, and total mass flow remain unchanged.
(3) mixture ratio of inner (fuel) to outer (air) flows.
(4) total mass flow at any combination of swirl numbers, velocity ratio, or mixture ratio.

Attention has been given for controlling those variables needed to support the theoretical effort. Thus, some geometry variations have also been considered:

(1) introducing disturbance in the flow in the form of a plate with holes (upstream of the swirl generations), in order to increase the turbulence level (in either the inner or the outer flow).
(2) changing the test section diameter, thus allowing for varying the flow rate (and Reynolds number), holding the flow velocity constant.

Planned operating conditions are as follows:

	flow rate (kg/s)	average speed (m/s)	Re	Swirl #
inner flow	0.01	10	20,000	from -1 to +1
outer flow	0.2	40	50,000	from 0 to +1

Final design considerations are being made now, and the various problems associated with air supply, exhaust system, etc. are being examined. Construction of the apparatus will start soon.

The laser Doppler velocimetry optics and data handling system are already operative and available for the study.

Theoretical Study

The development of a computational model to predict turbulent reacting axisymmetric shear flows with swirl has begun. The first step has been to make calculations on the plane turbulent shear layer between gases of different densities. Since more experimental data exists in the planar case, the comparison with calculations based upon certain turbulent modelling should be informative. The energy equation was included in the calculations so that the density gradient could be generated thermally or by species separation. Two different models were tried, the Imperial College k,ε model and Saffman's k,ω model. The equations were developed in two separate analyses using first Favre-mass-weighted averaging and then standard time-averaging with a gradient model for correlations of density with other quantities. The mixing layer profiles were found by assuming a similar solution exists and solving the resulting O.D.E.'s and also by solving the full P.D.E!s.

The results correctly predict qualitative trends but none of the models or methods used were capable of correctly predicting the mixing layer width on the density profiles. The k,ε model gives better prediction of the velocity profile shape while the k,ω model seem to predict better the maximum Reynolds stress. The Favre-averaged profiles gave better velocity profile shapes and mixing layer width predictions than did the standard time-averaged equations. In all cases, provided that $Le = 1$ and that the specific heats were independent of temperature as was to be expected, the results were the same independent of whether the density gradients were generated thermally or by species.

The models were developed under the assumption that the eddy length scale is much smaller than the mixing layer width. It has become apparent that some method of including the large scale eddies in the model is needed before attempting to model reacting flows. Three such methods are: 1) the use of an intermittency or conditional averaging method; 2) the inclusion of additional production and dissipation terms in the present models and 3) use of time-dependent equations. Once satisfactory modelling of the non-reacting case is achieved, work on reacting flows will begin with first considering simple one-step chemical kinetics.

III. MEASUREMENTS

TURBULENT STRUCTURE DETERMINATION BY RAMANOGRAPHY

Yale University, New Haven, Connecticut
Subcontract No. 8960-29

Professors R. K. Chang and B. T. Chu, Principal Investigators
Mr. M. Long, Assistant in Research
Mr. B. Webber, Assistant in Research

Introduction

The long-term objective of our research is to develop new spectroscopic techniques which are capable of providing fundamental information in the areas of turbulence and combustion. We are presently using the following techniques to measure the two-dimensional (2-D) concentration profile within the flow-field of a jet: 1) Mie scattering from aerosols seeded in the jet to obtain the 2-D instantaneous (9 μsec) concentration profile; 2) spontaneous Raman scattering to obtain the 2-D average CH_4 concentration profile.

Discussion

Mie Scattering

If we assume that the concentration profile of aerosols in a flow-field is representative of the gas concentration profile, an instantaneous "picture" of the Mie scattering from a plane intercepting the flow-field of a jet can provide information on the spatial distribution of the gas concentration. The argon ion laser light is focused in one dimension by a 25 cm focal length cylindrical lens giving a sheet of illumination 1 cm x 1 cm x 100 μm passing through the center of the jet. The axisymmetric jet used in the experiment is a preliminary design with a diameter of 2 mm and is seeded with sugar aerosols (less than 1 μm in

diameter) produced by an aerosol generator (Sierra Instruments Model 7330). The Mie scattered light is collected normal to the illuminated sheet by a lens and is focused on the face of the TV camera (PAR OMA 2 with SIT detector head) by another lens. The TV camera is electronically gated on for 9 μsec by a high-voltage pulser. The 2-D image is divided into a 100 x 100 element array and the digitized information is stored in a PDP 11/34 computer which controls the entire experiment.

From the instantaneous 2-D Mie intensity recordings, we were able to obtain the following properties of the jet at a Reynolds number of 4400: 1) Average 2-D concentration $\overline{C}(x,z)$ [x-axis along the jet downstream direction and z-axis in the illuminated sheet] obtained from 60 instantaneous concentration pictures. 2) Average 2-D non-dimensionalized concentration contours, $\overline{C}(x,z)/C_{max}(x)$, where $C_{max}(x)$ is the maximum concentration at distance x downstream. 3) 2-D rms concentration fluctuation with 60 instantaneous concentration pictures. 4) Spatial correlation in the concentration fluctuation in the z direction for a specific point along z and at fixed x values. Details of our results have been submitted for publication. In the future, we will test a technique devised to obtain both the spatial and the temporal correlation in the concentration fluctuation.

Raman Scattering

Ramanography has the disadvantage that Raman scattering from gases is much weaker than Mie scattering from seeded aerosols in the flow-field. The major noise source in Ramanography is photon shot noise, while that for Mie scattering is from marker shot noise caused by the small number of aerosol particles per unit volume.

The Raman scattered light from a 2-D illuminated sheet formed by the laser focal volume (1 cm x 1 cm x 100 μm thick) was too weak to detect. In order to increase the scattered light intensity, a quasi 2-D sheet formed by having the laser track undergo multiple reflection from two concave cylindrical mirrors was used. The resultant Raman scattering intensity from the CH_4 jet was detected by a cooled SIT TV camera. This quasi 2-D intensity profile must be normalized by the spatial inhomogeneity of the "striped" illumination sheet, collection optics throughput, and camera response. This normalization makes it possible to deduce the average CH_4 concentration within the 2-D sheet.

In order to obtain the instantaneous quasi 2-D Raman intensity profile, we have been working on stretching a conventional Q-switched laser pulse (30 nsec) to 1 μsec in order to avoid laser-induced air breakdown associated with high intensity pulses. A stretched Q-switched pulse is being generated by inserting a CdS (two-photon absorber) crystal within the rotating prism laser cavity. To obtain the needed laser energy (about 10 Joules), we may need to use a ruby amplifier to increase the energy provided by the pulse stretched ruby laser oscillator.

Semi-Annual Progress Report

CARS INVESTIGATIONS IN SOOTING FLAMES

United Technologies Research Center
East Hartford, Connecticut 06108
Subcontract 8960-28

Alan C. Eckbreth, Principal Investigator

Introduction

Laser Raman spectroscopic techniques for combustion diagnostics have undergone considerable development in the past several years and are now being employed in a variety of fundamental flame investigations. Instrumentally however, practical combustion devices possess flame environments which differ markedly from those typically (laminar premixed, hydrogen diffusion) employed in fundamental studies. Practical devices contain flames which can be highly particulate laden and hence, luminous, if hot, and turbulent. These conditions lead to a variety of severe, naturally occurring or laser induced interferences which must be overcome. Of these, laser modulated particulate incandescence appears to be the most severe. When the soot particulate loadings become moderate, on the order of 10^{-8} gm/cm^3 or larger, the spontaneous Raman signal to laser modulated soot incandescence interference ratio can become unacceptably low for measurement purposes.

Coherent anti-Stokes Raman spectroscopy (CARS) appears as an attractive alternative to spontaneous Raman scattering for practical combustor diagnosis. First, the CARS process generates signals generally several orders of magnitude greater than those possible with spontaneous Raman scattering. Second, the CARS radiation emerges as a coherent beam which can be completely collected using high f number collecting optics and spatial filtering. This not only leads to high signal collection efficiency, but low interference collection as well due to the greatly reduced solid angles employed. CARS signal strengths appear adequately large to overcome interferences from both natural background luminosity and laser modulated particulate incandescence. However, CARS generation in sooting flames had not been demonstrated. In sooting flames, there is the potential for the generation of nonlinear interferences from soot particulates and soot vaporization products. The objective of the present research is to address CARS generation in

sooting flames, to examine and develop techniques to suppress nonlinear interferences, and to perform CARS temperature measurements in such flames. Such a program logically precedes measurement attempts in actual research scale combustors.

Discussion

As described in the previous semi-annual report, CARS generation has been studied in a laminar, sooting, propane diffusion flames. Both coherent and incoherent interferences were encountered in the N_2 CARS bands from C_2 produced by the laser vaporization of soot using a 5320 Å pump laser. By reducing the bandwidth of the Stokes laser and using a polarization filter, these interferences were suppressible, and interference-free BOXCARS (Ref. 1) spectra of flame N_2 in highly sooting flames have been obtained. BOXCARS spectra from sooting flames have been recorded at moderate spectral resolution (~ $1cm^{-1}$) which rival clean, premixed flame spectra. Computer fitting of these spectra permits, in principle, measurement of the local flame temperature. Major emphasis during this period has been placed on assessing the temperature measurement accuracy of CARS thermometry. Initially, the accuracy of CARS thermometry has been assessed in a series of clean flame measurements. Experiments are currently in progress to measure sooting flame temperatures indendently.

CARS spectra from N_2 in clean flames were obtained at 1610^oK and 2110^oK from 7.5 cm and 2.5 cm dia hypo-tube burners operating on premixed methane-air mixtures. Temperatures were determined using either 0.0075 or 0.0125 cm dia Pt/Pt-10% Rh thermocouples coated with a mixture of 90% Yt_2O_3/10% BeO. The radiation corrections were obtained experimentally via sodium line reversal. Sodium was introduced in such a manner that the local flame temperature perturbation was less than 25K. The radiation corrections were not scaled but were determined at several wide ranging flame temperatures. Computer fitting the CARS spectra using a constant Raman linewidth code gave CARS temperatures of 1650^oK and 2150^oK respectively, i. e. the CARS temperatures were approximately $40^o K$ above those indicated by the radiation corrected thermocouples. The agreement between the experimental and computed CARS spectra was very good. Details of this work are contained in Ref. 2.

In an effort to avoid the requirement to spatially invert emission-absorption data for axisymmetric sooting diffusion flames, considerable effort was expended to produce a one-dimensional sooting flame which would permit application of reversal techniques. To date, we have not been satisfied with the degree of one dimensionality obtained or with the spatial stability of such flames. Currently two approaches are being evaluated. The first involves attempting sodium injection and sodium line reversal temperature determinations on the axis of a sooting diffusion flame. The second involves a soot reversal temperature measurement

at the tip of the flame where temperature gradients in the soot should be modest. When a satisfactory classical temperature measurement has been performed in the sooting flames, CARS spectra will be obtained and the temperature measurement accuracy assessed.

In the past, laser induced soot emissions were examined at discrete spectral locations using narrowband interference filters. Experiments are presently in progress to scan a substantial portion of the visible spectrum (i.e. 4000-7000 Å) with the aim of examining the laser induced emissions in greater detail. It had also been conjectured or inferred previously, that the laser induced Swan emissions decrease with Stokes laser bandwidth when performing CARS at 5320 Å and from N_2. Experimentally the effect of the Stokes laser bandwidth on the laser induced Swan emissions is being examined to ascertain whether this is indeed correct.

Considerable time was also expended in adapting the OMA (optical multichannel analyzer) to the 1-m double monochromator. This will decrease substantially the amount of time required for good average spectral determinations in laminar flames and permit single pulse thermometry in unsteady situations. Very nice spectra have been obtained, but some work remains to be performed to eliminate spectral variations caused by slight misalignments of the vidicon detector head. Once satisfactory operation is obtained, temperature field mapping in spatially structured flames will be greatly expedited.

References

1. Eckbreth, A. C.: BOXCARS: Crossed-Beam Phase-Matched CARS Generation in Gases Appl. Phys. Letters, Vol. 32, pp. 421-423, April 1978.

2. Eckbreth, A. C. and R. J. Hall: CARS Diagnostic Investigations of Flames. To be presented at the 10th Materials Research Symposium on Characterization of High Temperature Vapors and Gases, National Bureau of Standards, Gaithersburg, Maryland, September 18-22, 1978.

61

LASER RAMAN PROBE FOR COMBUSTION DIAGNOSTICS

General Electric Company, Corporate Research and Development
Schenectady, New York
Subcontract No. 8960-17

Marshall Lapp, Principal Investigator
C. M. Penney, Physicist
S. Warshaw, Physicist

Introduction

Various correlations of fluctuation values of temperature, gas density, and velocity are of importance in analyses of turbulent combustion flows. We have focused our current research efforts upon obtaining such information; thus, experiments are in progress to acquire essentially simultaneous temperature and axial velocity data for a turbulent co-flowing jet combustor, and plans are underway for extending the probe system to include simultaneous values of product gas density.

Discussion

Our major effort during this past reporting period has been in adapting our independent vibrational Raman scattering (VRS) and laser velocimetry (LV) probes into a unified system, compatible for significant measurements on a turbulent diffusion flame. Various measurement problems have arisen during the course of this work which have resulted in a variety of redesign efforts for the optical measurement systems and the laser source. The result of this work is that we now have an operating integrated VRS-LV system utilizing a spectrometer for Stokes/

anti-Stokes VRS temperature data and a backscatter LV system for axial velocity data, with overlapping measurement volumes.

The fluctuation temperature data is produced from Raman signals induced by scattering from a nominally 1.2 to 0.6 J pulsed laser beam from a modified Phase-R flashlamp-pumped dye laser. Additional alterations have been made to this laser source in order to correct internal electrical breakdown problems within its pulse circuitry and also to extend the dye lifetime (and therefore the number of laser shots between dye replenishments). Current operation permits up to about 200 shots before refilling. Laser linewidth and spectral position are monitored by an online TV monitor displaying the laser spectrum obtained for each shot by use of a small ancillary spectrometer with TV camera detector.

The VRS signals are detected with photomultipliers, utilizing a Spex 0.75-m grating polychromator with 1 mm wide by 2 mm high entrance slits and 3 mm wide exit slits in the Stokes and anti-Stokes spectral channels. The exit slit widths correspond to 3 nm measured spectral widths, and are tailored to the required passbands of the N_2 Stokes and anti-Stokes signatures utilized for temperature determinations. The incident laser beam and the Raman collection optics define a test zone of roughly 0.8 mm along the beam (i.e., parallel to the spectrometer slits) x 0.2 mm x 0.2 mm.

The axial velocity is determined through use of a Thermo-Science Inc. counter burst processor dual-fringe LV unit. The optics are arranged in a backscatter configuration, and define a roughly ellipsoidal measurement zone whose dimensions are approximately 0.6 mm along the data acquisition axis, x 0.2 mm x 0.2 mm.

The combustor used for these experiments is a fan-driven coaxial jet combustor, with a 3 mm-diameter fuel tube surrounded by a 100 mm-diameter

air pipe. Optical access for the pulsed laser source used for the VRS data is via Brewster's angle windows attached to small side tubes surrounding 7 mm-diameter access holes. The VRS signals as well as the LV source and response signals pass through the air pipe surface.

The accuracy of the present measurement system is determined primarily by two factors, viz, the VRS measurement accuracy (which is inevitably less than that for the LV) and the spatial and temporal simultaniety of the two measurement systems. The VRS temperature data are determined to about 5-7% in this particular system, based upon experimental temperature spread function determinations corroborated by detailed theoretical estimates.

The spatial accuracy of the present configuration of VRS and LV optics is limited; only partially coincident test zones are utilized, since the major axes of their respective measurement zones are now orthogonal. This is an experimental artifact, resulting from spatial limitations of the apparatus mounts, and will be modified in a planned apparatus redesign to provide significantly closer coupling of these test zones.

The temporal simultaneity of the data acquisition is characterized by a time delay of roughly 25 μs between the LV and VRS signals, which we consider adequate for these experiments. Utilizing a new laser source (anticipated within the next contract period), this time delay can be shortened to roughly 1/4 of the present value through use of improved laser triggering. (A higher pulse repetition frequency will also improve the data rate.)

Within the framework of these experimental limitations, certain specific experimental advantages should be borne in mind. Firstly, the VRS

data are obtained with spectrometer detection apparatus, which permits detailed optical background spectral data to be acquired which are not easily obtained without use of such apparatus. Such data on the background is essential in order to produce VRS data defined by its ultimate measurement capabilities for any given optical detection configuration.

Secondly, the VRS apparatus has been designed with the goal of compatibility between the present photomultiplier optical detection and imminent implementation of multiple-spectral-channel silicon diode array optical detection. This has been accomplished through use of a polychromator attachment to the basic spectrometer, which permits either mode of detection to be employed. Preliminary flame spectra have been obtained using this advanced form of detection. Finally, the VRS and LV instrumentation have been designed for implementation of microcomputer control, with digital data acquisition for all the essential experimental parameters.

The present VRS and LV system can be optimized further by better definition of the spatial and temporal measurement accuracy, but in its present state serves well to demonstrate the overall instrumentation capability and to provide approximate correlated temperature and velocity data. These data are presented in the form of probability distribution functions (pdf's, or histograms) of the independent and coupled variables for spatial locations in the turbulent diffusion flame for which previous independent variable experimental data for this combustor configuration are available. These pdf's give far more useful information than the mean or rms values which can be obtained from them, since they present the detailed fluctuation data necessary for proper treatment of detailed chemical and fluid mechanic flame properties.

Notes and References

Recent publications and manuscripts related to this research effort supported by Project SQUID and by other parallel General Electric and government efforts are listed below:

1. M. Lapp, "The Study of Flames by Raman Spectroscopy," in Proceedings of the Sixth International Conference on Raman Spectroscopy, Vol. 1, ed. by E. D. Schmid, R. S. Krishnan, W. Kiefer, and H. W. Schrötter (Heyden and Son Ltd., London, 1978), p. 219.

2. M. Lapp and C. M. Penney, "Instantaneous Measurements of Flame Temperature and Density by Laser Raman Scattering," to appear in Proceedings of the Dynamic Flow Conference 1978 - Dynamic Measurements in Unsteady Flows, Baltimore, September 18-21, 1978.

TUBULENCE MEASUREMENTS

IN JETS FLAMES AND COMBUSTORS

Polytechnic Institute of New York
Aerodynamics Laboratories

Subcontract No. 8960-5

S. Lederman - Principal Investigator

Introduction

In the last semiannual report of April 1, 1978, data concerning concentration of species, their temperature, concentration and temperature fluctuation, the velocity and turbulence intensity in a methane CO_2 and air flame, as well as in a flame with the addition of carbon particles, using spontaneous Raman scattering have been obtained. Furthermore, concentration of minor species in a sooty flame using CARS have been measured. In the present reporting period an attempt has been made to compare some of the experimental results using Spontaneous Raman and LDV measurements with theoretical and experimental data obtained using conventional techniques.

Discussion

As has been pointed out in the preceding semiannual report and discussed in Reference 1-9, the applicability of the spontaneous Raman effect to the nonintrusive diagnostics of flow fields encountered in combustion and propulsion provided a major part of the development effort in our own and many other laboratories for the last several years. It has been shown, Reference 1 that this technique is capable, under proper conditions, of providing most of the pertinent experimental data, such as temperature, species concentration and derived data, such as correlation and cross-correlation parameters. Some general experimental data corresponding to the above, on jets and flames have been presented in Reference 1. In this reporting period an attempt has been made to compare the data obtained by the optical methods, i.e., Raman and Doppler with theory and other available experimental data obtained by conventional means, and thus confirm or disprove the applicability of the spontaneous Raman and Doppler techniques at least on laboratory scale jets and flames

In Figure 1 an example of the normalized data obtained in our laboratories, on a single axisymmetric cold jet is presented. In the same Figure experimental data obtained by Lan Morris and Fisher, Reference 10, Barrett and Giel, Reference 11 and by Harsher, Reference 12 who compared his theoretical results with data from Maestrello and McDaid, Reference 13. Note that the

turbulent intensities of Reference 10 and 11 compare to our own turbulence intensity with some slight displacement which can be explained by the differences in the initial condition on the jet which are not given in full detail. Figure 2 indicates some specie concentrations in our cold axisymmetric jet. Figure 3 indicates the species cross-correlation of the first and second kind. No equivalent data is available in the literature to our knowledge. Figure 4 shows the velocity distribution of a methane air flame. The data obtained in our laboratories are compared to the data of Chigier and Strokin, Reference 14. In the same figure the coaxial cold jet data are compared with the coaxial cold jet data of Chigier and Strokin, as well as the data of Chigier and Beer, Reference 15 and Peter, Chris and Paulk, Reference 16. The same figure shows normalized concentration data in a flame as measured with the Spontaneous Raman technique in our laboratories and data of Chigier and Strokin measured by chromatography. It is evident that there is a certain discrepancy between the two sets of data. At this point it can only be said that the sampling probe method may not be the most reliable in this kind of an environment. It must however be noted that the normalized concentration obtained by the Raman method appears to follow the same hyperbolic type of concentration profile as obtained by Chigier and Strokin on a cold jet.

References

1. Lederman, S. and Celentano, A.: "Application of the Integrated Raman and LDV System". Polytechnic Institute of New York, M/AE Report No. 78-5. Project SQUID Report PIB-35-PU.

2. Lederman, S.: "The Use of Laser Raman Diagnostics in Flow Fields and Combustion". Progress in Energy Comb. Sci., 3, pp. 1-34, 1977, Pergamon Press.

3. Lederman, S.: "Temperature, Concentration Velocity and Turbulence Measurement in Jets and Flames". Technical Report No. PINY-76-10 December 1976, Project SQUID, Purdue University.

4. Lederman, S.: "Experimental Techniques Applicable to Turbulent Flows". AIAA Paper No. 77-213, Los Angeles, CA.

5. Lederman, S.: "Some Applications of Laser Diagnostics to Fluid Dynamics", AIAA Paper No. 76-21.

6. Lederman, S.: "Raman Scattering Measurements of Mean Values and Fluctuations in Fluid Mechanics". Laser Raman Gas Diagnostics ed. by M. Lapp and C. M. Penney, Plenum Press, N.Y., pp. 303-310, 1974.

7. Lederman, S. and Bornstein, J.: "Temperature and Concentration Measurements on an Axisymmetric Jet and Flame". Technical Report No. PIB-32-PU, December 1973.

8. Lederman, S. and Bornstein, J.: "Application of Raman Effect to Flow Field Diagnostics". Progress in Astronautics and Aeronautics, 34, "Instrumentation for Airbreathing Propulsion".

9. Lederman, S. and Bornstein, J.: "Specie Concentration and Temperature Measurements in Flow Fields". Technical Report No. PIB-31-PU, March 1973.

10. Lan, J.C., et. al.: "Turbulence Measurements in Subsonic and Supersonic Jets Using a Laser Velocimeter". AIAA Paper No. 76-348.

11. Barnett, D.O. and Giel, T.V.: "Laser Velocimeter Measurements in Moderately Heated Jet Flows". AEDC TR-76-156.

12. Harsher, P.T.: "A General Analysis of Free Turbulent Mixing". AD 778-414

13. Maestrello and McDaid: "Free Turbulent Shear Flows". NASA SP-321 (Case No. 6).

14. Chigier, N.A. and Strolein, V.: "Mixing Processes in a Free Turbulent Diffusion Flame". Combustion and Science, Vol. 9, p. 111-118, 1974.

15. Chigier, N.A. and Beer, J.M.: "The Flow Region Near the Nozzle in Double Concentric Jets". ASME Journal of Basic Engineering., pp. 797-804, December 1964.

16. Peters, C.E., Chriss, D.E., Paulk, R.A.: "Turbulent Transport Properties in Subsonic Coaxial Free Mixing Systems". AIAA Paper No. 69-681.

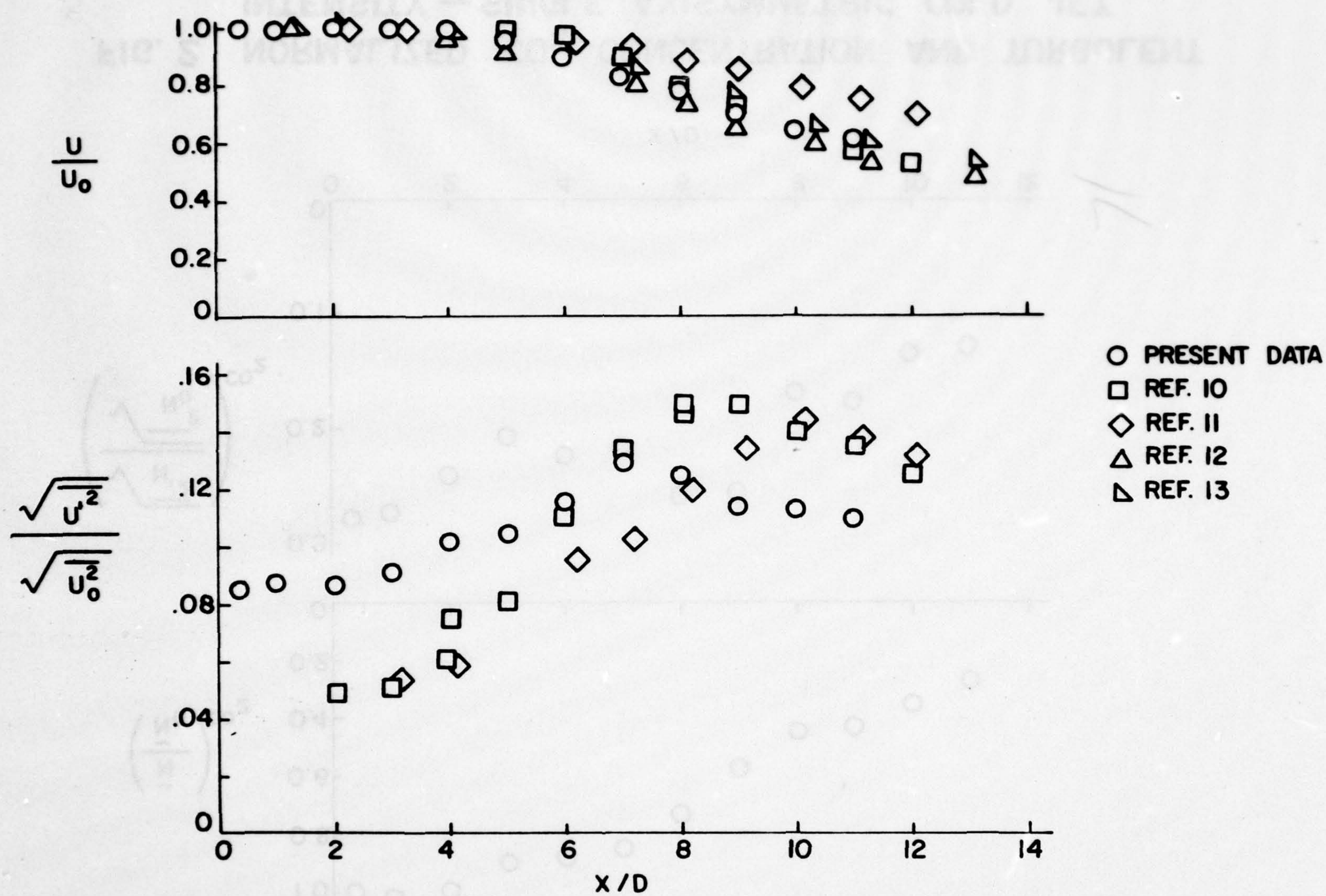


FIG. 1 NORMALIZED VELOCITY AND TURBULENT INTENSITY - SINGLE AXISYMMETRIC COLD JET

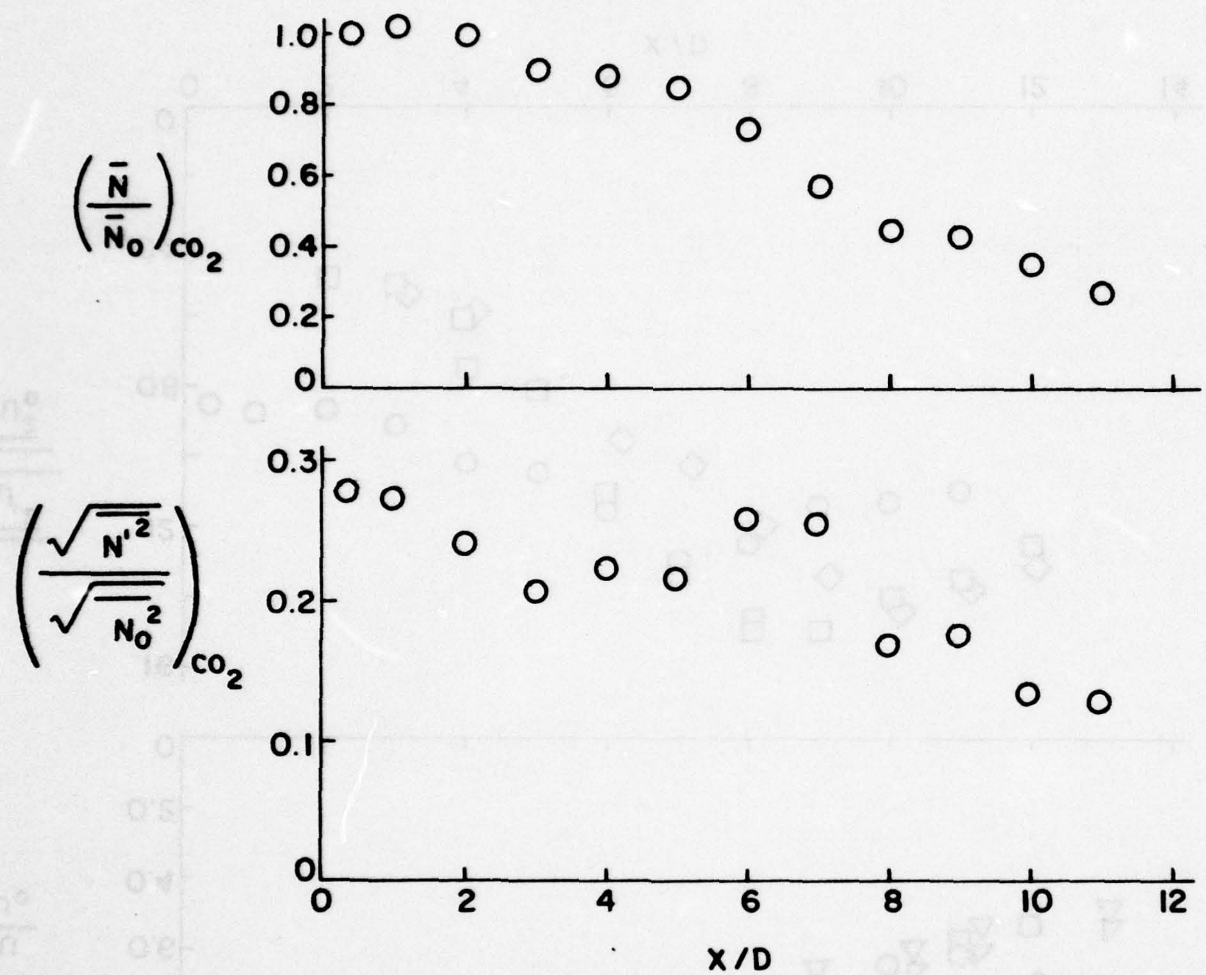


FIG. 2 NORMALIZED CO_2 CONCENTRATION AND TURBULENT INTENSITY — SINGLE AXISYMMETRIC COLD JET

81

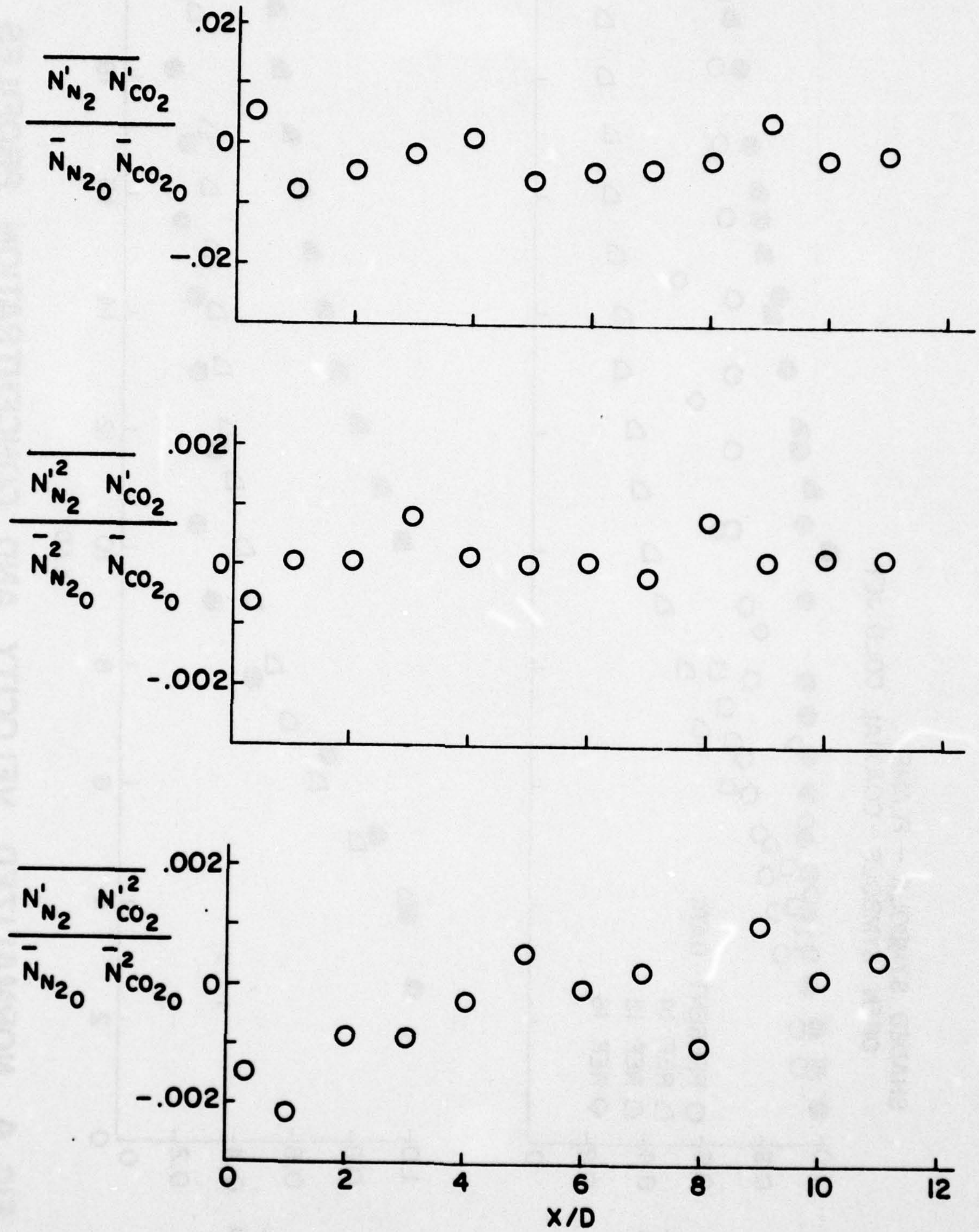


FIG. 3 SPECIE CONCENTRATION 1st AND 2nd CROSS CORRELATION - SINGLE AXISYMMETRIC COLD JET

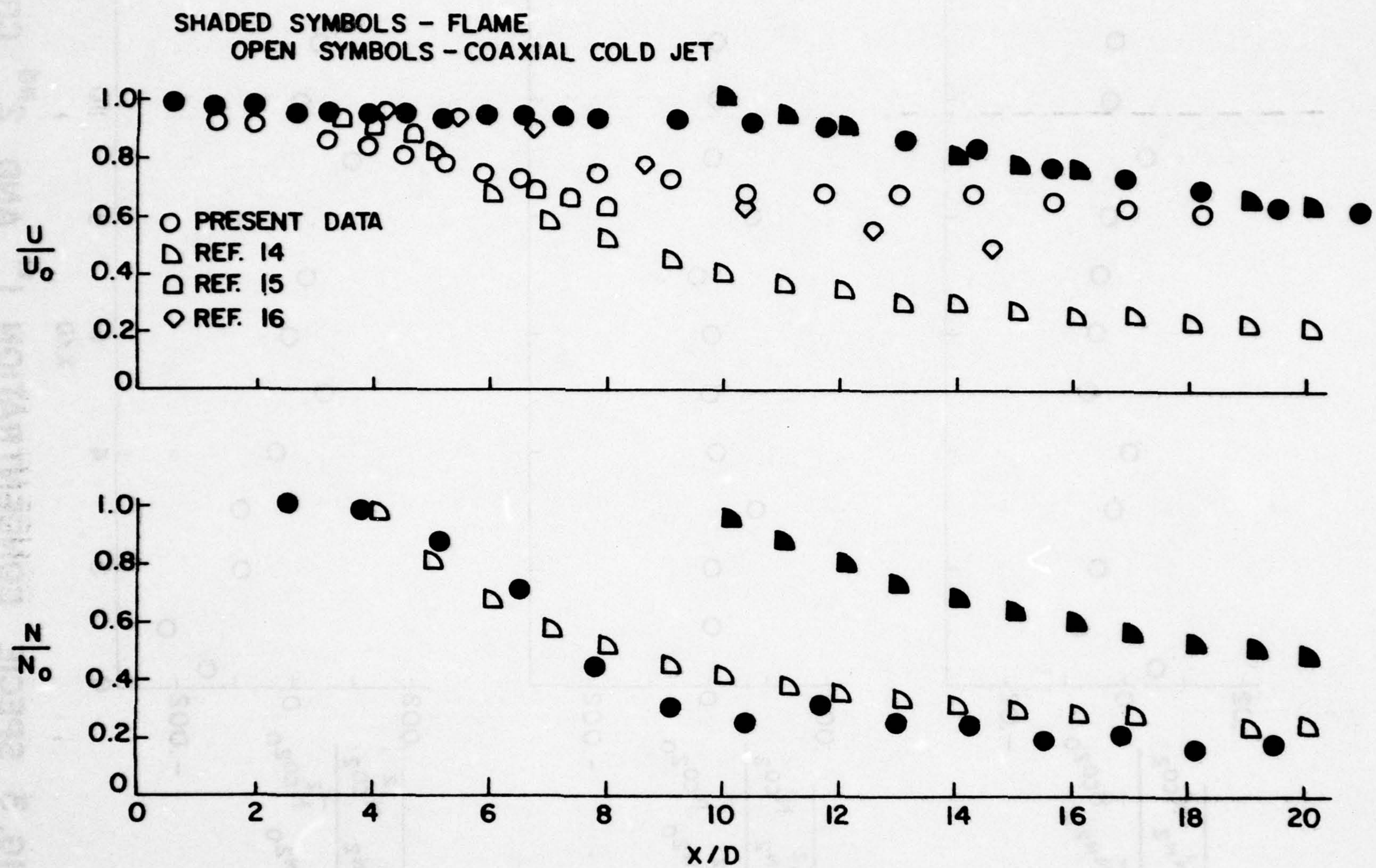


FIG. 4 NORMALIZED VELOCITY AND CONCENTRATION PROFILES IN A METHANE-AIR FLAME AND A COAXIAL COLD AIR-AIR JET

IV. TURBULENCE

Semi-Annual Progress Report

LARGE SCALE STRUCTURE AND ENTRAINMENT IN THE TURBULENT MIXING LAYER

University of Southern California, Los Angeles, California
Subcontract No. 8960-12

Professor F. K. Browand, Principal Investigator
Mr. B. O. Latigo, Research Assistant

Introduction

Previous visual observations indicate the presence of large scale, quasi-organized, vortical lumps aligned across the flow (LSS) in the two dimensional mixing layer. The existence of these structures--documented visually over a range of Reynolds numbers extending from 10^3 to 10^7 -- is suggestive of their importance as a characteristic feature of the turbulent flow. As the mixing layer grows downstream the vortices must necessarily interact to form larger vortices. The interactions-- to a certain degree--are distinct and repeatable, and it is precisely these interactions which are responsible for the growth of the mixing layer. The present experimental study, carried out in a wind tunnel at Reynolds numbers 10^6, is intended to provide more information about this large scale structure.

Discussion

The procedure for studying large scale structure has been to form an ensemble average of individual interactions to produce a composite interaction. A series of small speakers are placed in the roof of the wind tunnel immediately above the splitter plate trailing edge. They produce an acoustical perturbation at the trailing edge which is reasonably uniform across the span of the tunnel. We believe this disturbance

augments the naturally occurring interactions without altering their fundamental character.

A series of u and v velocity measurements has recently been completed. These measurements were made by slowly traversing an x-wire across the flow at a number of stations in the downstream region between $x = 17$ inches and $x = 40$ inches, (Reynolds numbers, $\Delta U x/\nu$, from 620,000 to 1.5×10^6). The forcing is a series of four acoustic pulses which produce four well-defined vortices in the region just downstream of the plate trailing edge. Figure 2 shows the path of these vortices in an x-t plane obtained from the conditioned velocity information. (Actually five vortices are produced, but the leading vortex does not interact with others in the region of interest.)

One immediate objective is to assess the dynamical importance of the large scale structure by determining, for example, how these interactions contribute to the overall production of net Reynolds stress. It was mentioned in the last progress report that a major part of the Reynolds stress production can be attributed to the interactions between the large scale features. Some of the details of how this Reynolds stress production is achieved are now becoming clear, although the results are still being analyzed and interpreted. A typical interaction sequence is sketched in figure 2. When an interaction occurs, the downstream (larger) vortex moves upward carrying relatively high momentum fluid to the low speed side. The upstream (smaller) vortex moves downward carrying relatively low momentum fluid to the high speed side. An example of this is shown in figure 3, recorded at a downstream position of $x = 30$ inch. Here the interaction is between the fourth vortex and the combined first, second and third, which have paired previously (see figure 1). Figure 3 shows 13 time traces recorded at different vertical positions across the mixing layer. Each trace is the product of the ensemble averaged vertical and longitudinal velocities averaged over 256 individual passages. The product, $u'_E v'_E/(\Delta U)^2$ can be interpreted as the contribution of the large scale vortical features to the perturbation momentum flux. (The area under any curve is related to the contribution from the large scale interactions to the total time averaged Reynolds stress.) The first contribution in figure 3 is due to the leading (non-interacting) vortex. Its passage is associated with a positive momentum flux on high speed side only. The larger contribution, coming later in time, is associated with the interacting vortices. Several points of interest are:

i) The momentum flux becomes small and periodic as the free stream on either side is approached. Thus, the net contribution, integrated over a passage period, approaches zero as it must do in the irrotational flow.

ii) The peak contribution to the momentum flux, for this portion of the interaction, comes on the low speed side of the mixing layer. The peak on the low speed side appears earlier in time than the smaller peak on the high speed side. This suggests that the upward movement of the leading vortex occurs before the dowward movement of the trailing vortex.

iii) Large negative momentum fluxes are not observed. The momentum flux does change signs following the large, positive peaks, but these negative fluxes are quite small compared to the large positive fluxes. Thus, the significant transfer of momentum is always in the direction to increase the energy of the large scale structure.

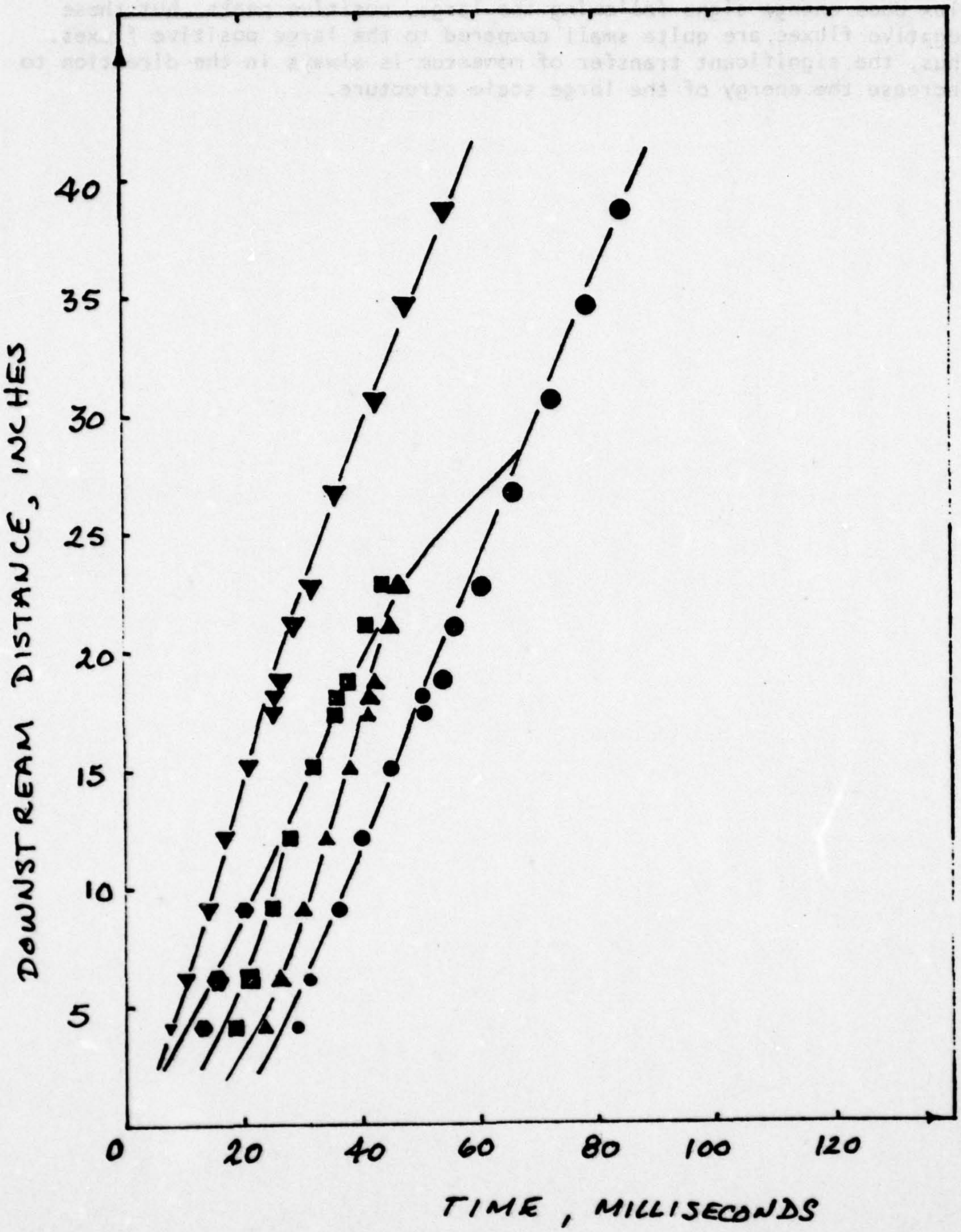


FIGURE 1. X-t PLOT OF VORTEX PATHS.

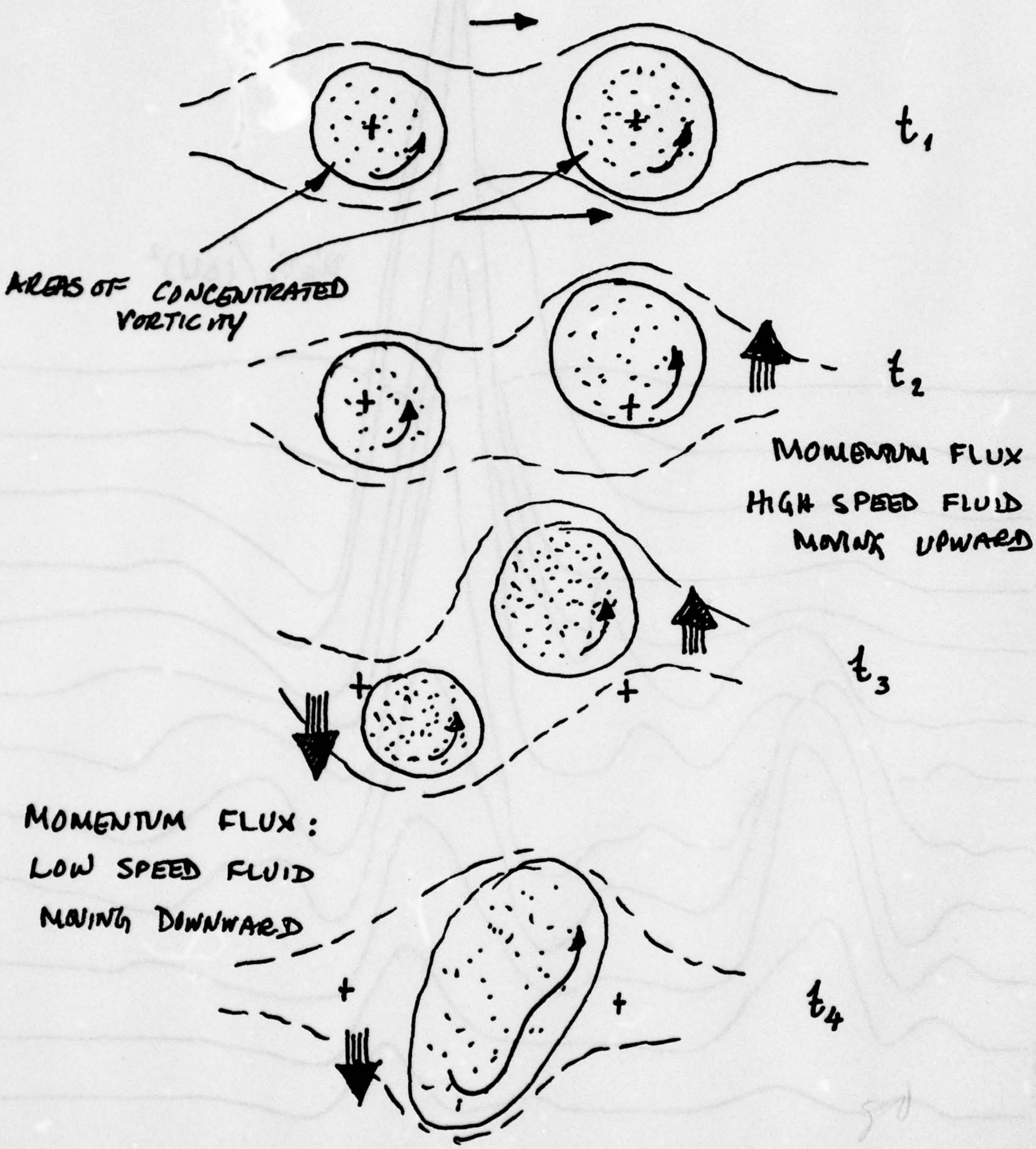


FIGURE 2. SKETCH OF INTERACTION STAGES AND TIMES OF LARGE MOMENTUM FLUX.

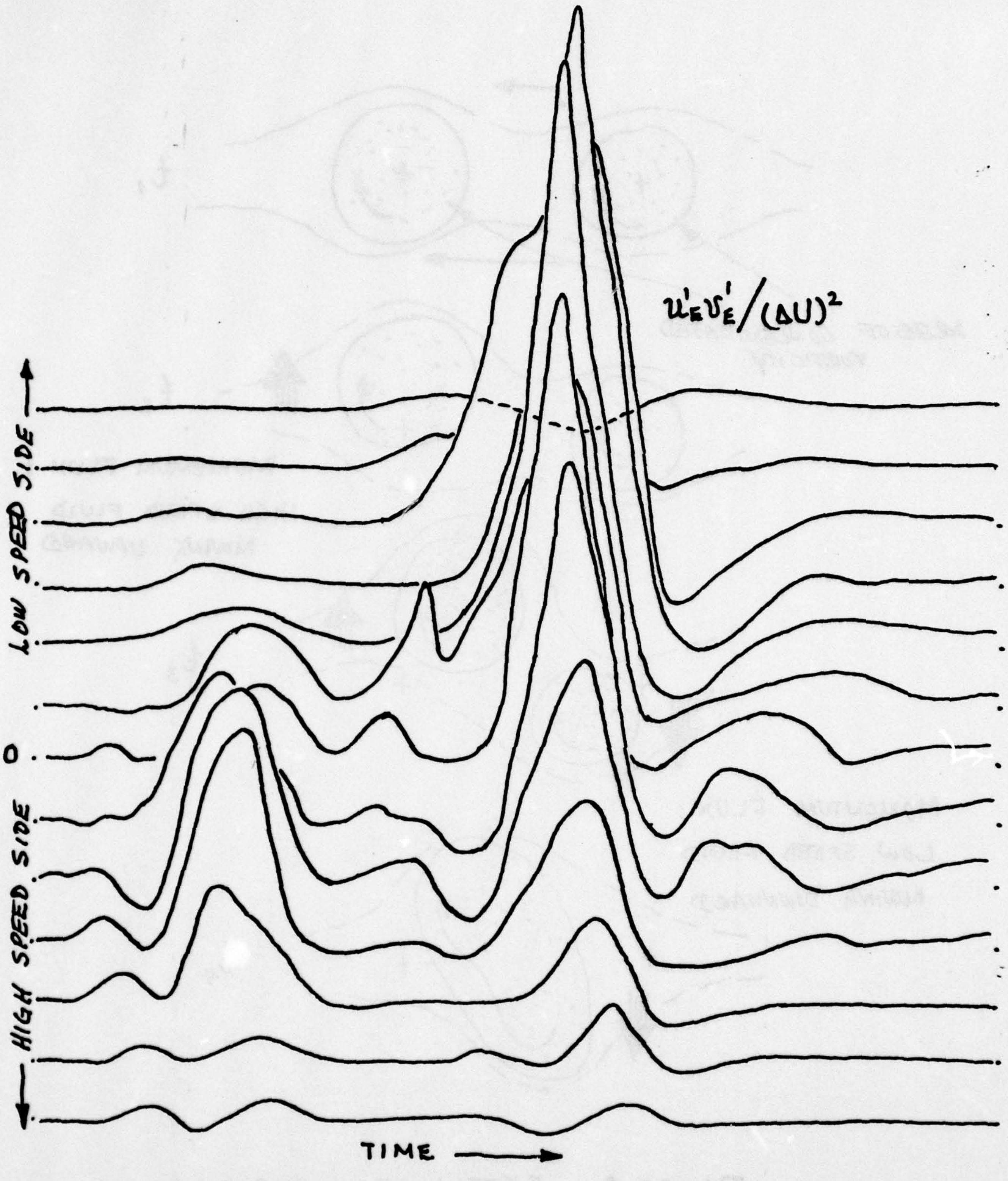


FIGURE 3. LOCAL MOMENTUM FLUX ASSOCIATED WITH THE LARGE STRUCTURE.

THE STRUCTURE OF EDDIES IN TURBULENT FLAMES

University of Sheffield, England
Subcontract No. 8960-30

Dr. N. A. Chigier, Principal Investigator
Dr. A. J. Yule, Research Fellow

Introduction

This investigation has the objectives of measuring the structure of turbulent flames and identifying and quantifying the roles of the large eddies in these flames. It is intended to achieve an improved fundamental understanding of the mechanics of turbulent combustion. Multipoint time resolved measurements of various quantities are processed by using conditional sampling and correlation techniques to measure eddy and reaction zone structure in axisymmetric diffusion flames. The data is compared with simultaneously acquired high-speed movies. Previous experiments have shown that large coherent eddies are found in non-reacting shear flows and there are many indications that similar structures exist in various types of combustor. These eddies will have a strong influence on mixing, as well as the other important characteristics of turbulence and it is essential that their physical structures are understood in order to permit improved modeling of turbulent combustion. These experiments provide information on the effects of large eddies on combustion and, conversely, the effects of combustion on eddy structure.

Discussion

During the first year of this investigation, apparatus has been constructed, as shown in Fig. 1. A 25.5 mm primary jet of gaseous fuel ejects into a 400 mm dia coflowing secondary stream of air. For accurate Laser Doppler Anemometry (LDA) measurements, both the primary and secondary flows must be equally seeded with

(SiO_2) particles. A major effort was required in order to achieve adequate seeding while, at the same time, maintaining low turbulence levels (1%) in both streams. The dense seeding required for velocity measurement with good temporal resolution results in the blocking of fine mesh screens, used for reduction in turbulence levels. The problem was solved by injecting particles downstream of these screens and carefully designing the flow downstream of injection. A new particle suspension system, with improved control of seeding by using a sound field to fluidize the particles, has been constructed and is in use. The complete plenum chamber can be traversed vertically and horizontally relative to the fixed LDA optics. Other traversing systems permit the independent positioning of various probes in horizontal and vertical planes.

The objectives of the experiment necessitate accurate measurement techniques with good spatial resolution and frequency response. The sophisticated data processing required for conditional sampling and correlation measurements necessitates that the LDA and all other probes are directly (and simultaneously) interfaced with the data analysis computer. Major improvements have been made to the signal validation logic in the LDA, so that instantaneous velocity can now be measured in the flames with an accuracy of 0.5%. Techniques for manufacturing and computer interfacing 25 μm Pt-20% Rh/Pt-40% Rh thermocouples have been developed. A minicomputer-controlled electrical overheating procedure permits in-situ measurement of the thermocouple response characteristics in the flame and measures the validity of the first order 'time constant' signal correction. A water-cooled ionization probe has been constructed. This probe is used to provide the triggering criteria for conditional sampling experiments based on the signal 'spikes' generated by fluctutating flame fronts.

In non-reacting turbulent shear flows, the large eddies are similar in form to the vortex-like structures generated upstream where the flow field is dominated by viscous effects. Evidence indicates that, in axisymmetric jets and mixing layers, the large turbulent eddies are derived directly from the transitional vortices generated near the lip of the nozzle. For a burning axisymmetric jet of gaseous fuel, this initial nozzle region is likely to be of even more importance because, firstly, flame stabilization is generally achieved in this region and, secondly, heat release will affect the instability mechanisms and, thus, the development, and probably the structure, of the turbulent flame region downstream. In addition, for the experimental data to be usefully interpreted in terms of combustion modeling, it is essential that the initial and boundary conditions of the flames are accurately measured.

For the above reasons, the first part of the measurement program is concentrating on the initial region of the flame. The relatively large burner diameter permits measurements with good spatial resolution in the initial, transitional flame region and also allows reasonably high Reynolds numbers to be achieved with relatively low velocities. A range of flames has been studied using high-speed photography. Initial measurements have been made in a flame with nozzle velocity $U_j = 6.3\ ms^{-1}$ and $U_j/U_s = 9$. The premixed propane/air volume flow ratio is 1:2.4, which is well

outside the flammability limits, so that the gas mixture burns as a diffusion flame in the surrounding secondary airstream. The total visible flame length is 1.5 m and the (cold flow) Reynolds number is 10^4. Movie films indicate that vortex rings are formed periodically near the nozzle and then rapidly break down three-dimensionally until the flow has the visual appearance of a turbulent flame after 0.5 m. The linear streaks evident during this breakdown are similar to those described previously for cold jets and are indicative of the presence of the same basic fluid mechanical phenomena (wave instability of vortices).

The low initial turbulence levels at the nozzle plane permit study of the natural development of the turbulent flame from instabilities in the initially 'laminar' mixing layer and also permit comparison between the burning case and the nonburning case. Figures 2-4 show data for the initial region of the jet under burning and nonburning conditions. Figure 2 shows that the jet potential core persists considerably beyond the four nozzle diameters typical for nonburning flows. The temperature data shows that peak temperatures are found on the outer side of the mixing layer. Comparison of mean and fluctuating velocity distributions for burning and nonburning cases at x = 100 mm, Fig. 3, clearly shows the important influence of reaction on the structure and development of the turbulent flow. In the transitional flow, the increase in viscosity as a result of heat release plays a dominant role. The equivalence ratio distribution across the mixing layer causes the reaction zone to be located on the low velocity side of the vorticity peak in the mixing layer. However, sufficient heat is diffused into this region of high vorticity, for increased viscosity to severely dampen the growth and instabilities of the transitional vortices, compared with the cold case (which is fully turbulent at this position). This damping results in reduced entrainment, so that the potential core, in the flame, extends much further from the nozzle than in the nonburning jet. Thus, the higher velocities across the central part of the burning flow are not caused by dilatation effects, but rather by reduced entrainment. The damping of the instability mechanism is evident in the low turbulence levels, seen in Fig. 3, for the burning case. Differences between the structures of the burning and cold jets are also indicated by velocity probability density distributions, shown in Fig. 4. The negative skewness on the inner side, and the positive skewness on the outer side of the jet are more pronounced for the burning flow and are indicative of intermittent flow.

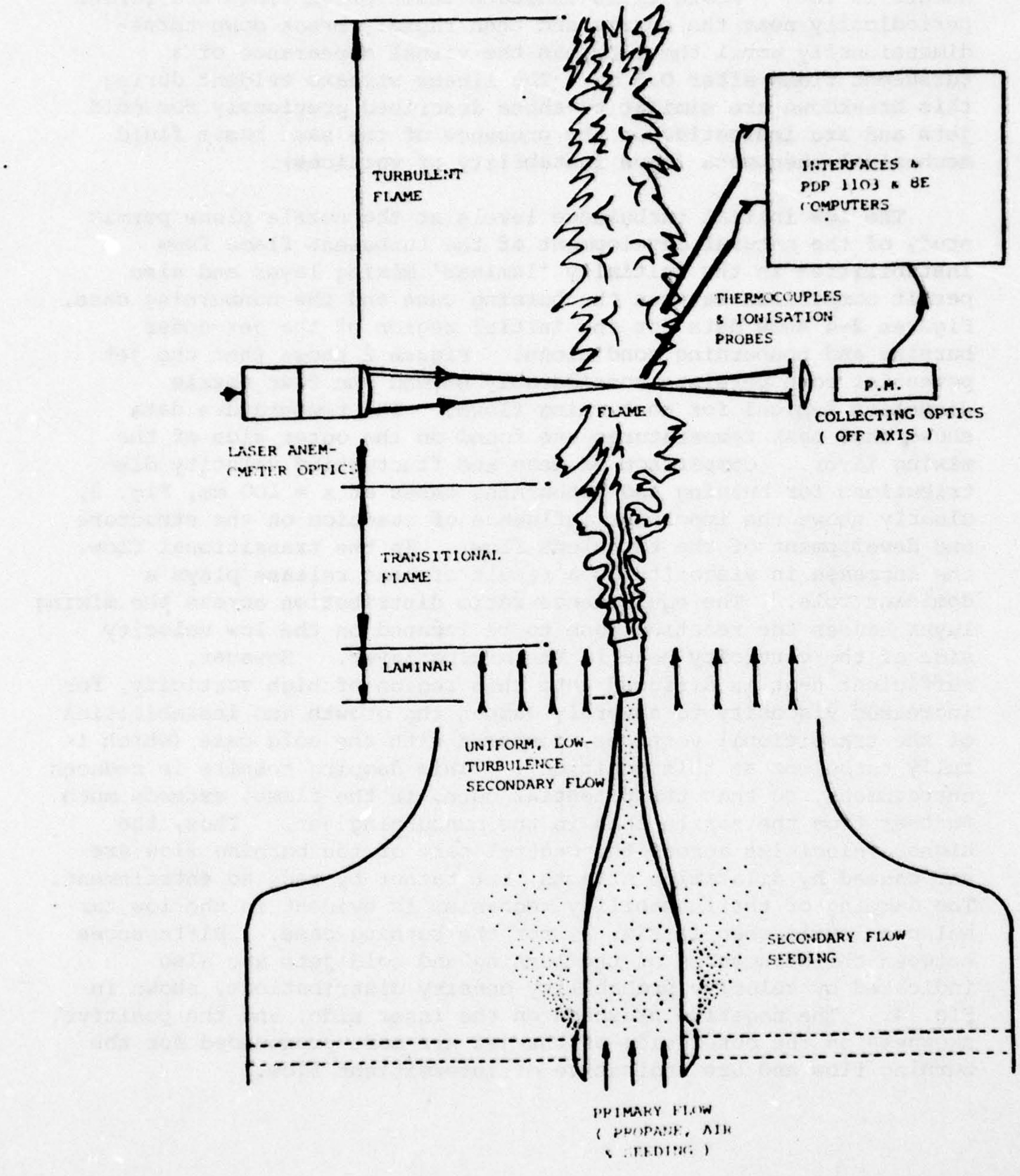


Figure 1. SCHEMATIC VIEW OF EXPERIMENT

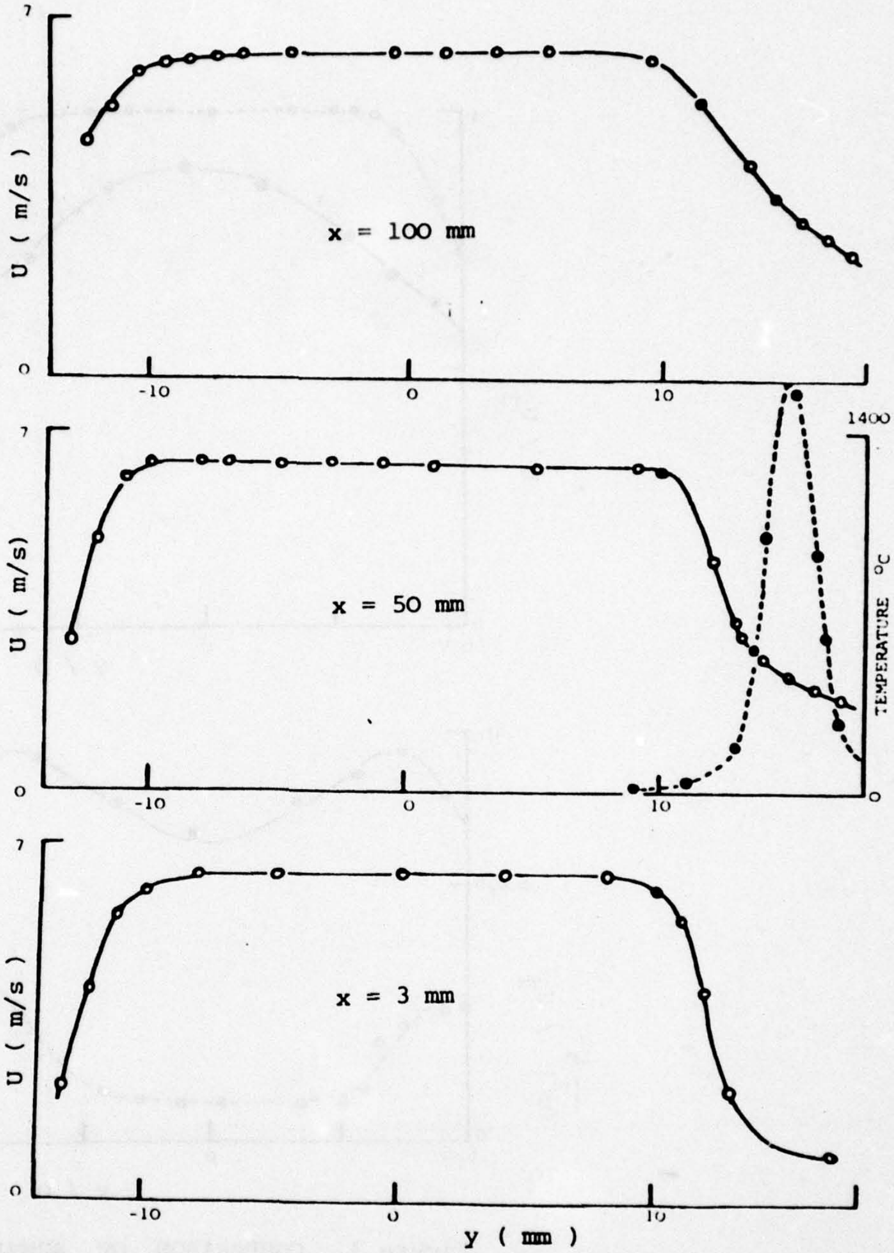


Figure 2. MEASUREMENTS IN INITIAL REGION OF FLAME

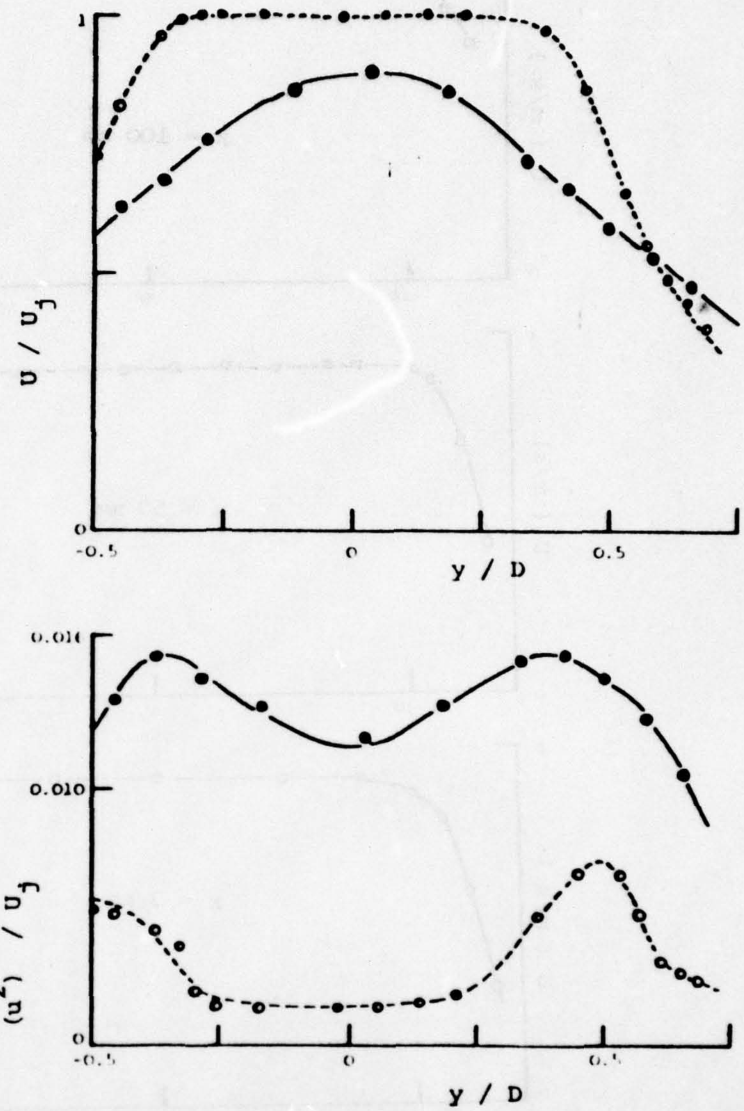


Figure 3. COMPARISON OF BURNING AND NON-BURNING FLOWS AT x = 100 mm; —●— NONBURNING, ---o--- BURNING

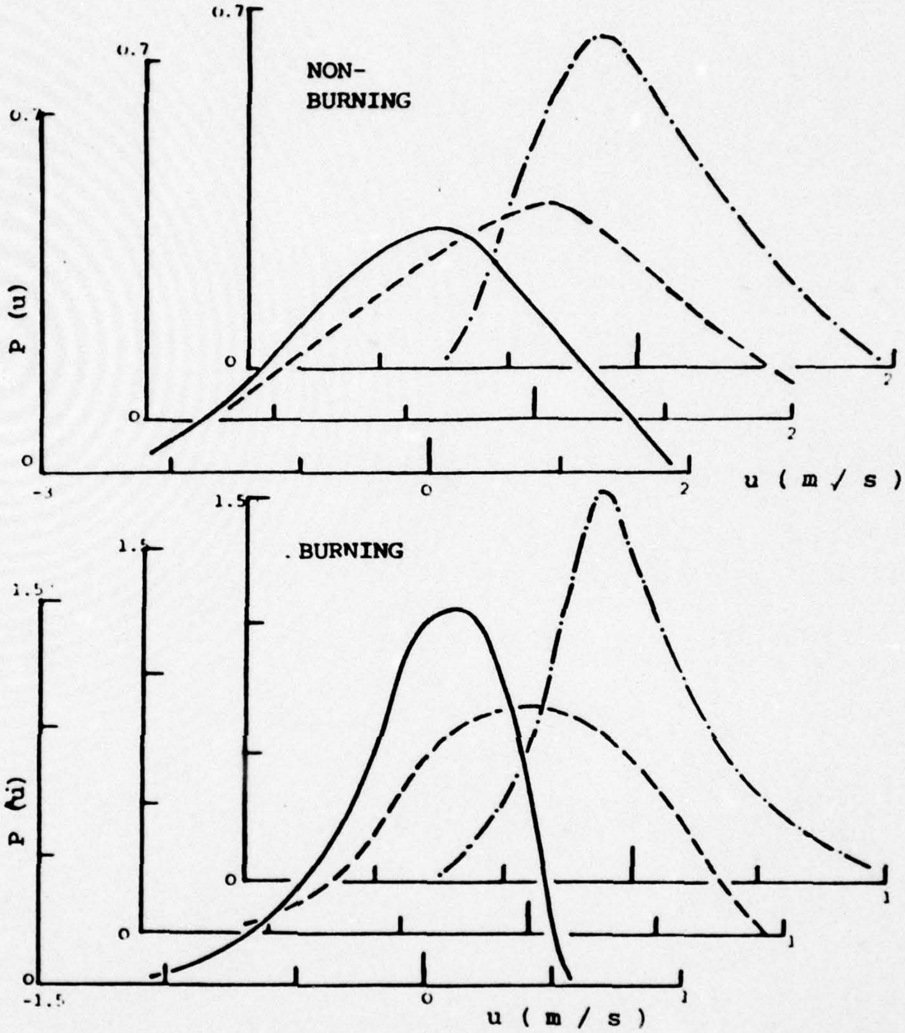


Figure 4. PROBABILITY DISTRIBUTIONS OF VELOCITY AT x = 100 mm FOR BURNING AND NONBURNING FLOWS;
——— U/U_1 = 0.96, ----- U/U_1 = 0.7, •——•—— U/U_1 = 0.5

Semi-Annual Progress Report

HETEROGENEOUS TURBULENT FLOWS RELATED TO PROPULSIVE DEVICES

University of California, San Diego
Subcontract No. 4965-26

Paul A. Libby
Principal Investigator

Introduction

This research addresses problems related to the turbulent heterogeneous flows which arise in a variety of propulsive devices when reactants and products mix and react. The effort is both experimental and theoretical; the experimental program concerns exploitation and extension of the multiple sensor "hot wire" technique of Way and Libby which permits time-resolved and space-resolved measurements of velocity and concentration of one light species, e.g., helium, in a mixture of light and heavy gases under isothermal conditions. The application of this technique in the present research is to a confined internal flow corresponding to an idealized combustor. The related theoretical work supports the experimental effort and attempts to extend the results thereof to flow situations of more practical concern, e.g., to chemically reacting flows.

Discussion

Our theoretical work continues to concern turbulent reacting flows involving premixed reactants and to be carried out in collaboration with Professor K.N.C. Bray and Dr. J.B. Moss of the University of Southampton. In our previous Progress Report we indicated that we were embarking on a study of the effect of acceleration on turbulent flames and that a new theory for such flames is required in order to account

properly for the effects of acceleration. The initial work on such a theory has been completed and reported in reference 1. The basis for the new theory is an extension of the Bray-Moss model for premixed combustion to include the joint probability density function for the velocity-product concentration. This extension combined with quite plausible assumptions regarding the pdf of the velocity for a given product concentration leads to a non-gradient theory of premixed combustion, a theory which readily permits incorporation of the effect of acceleration and at the same time assessment of gradient transport and other effects in turbulent flames.

All current theories of turbulent reacting flows depend on gradient transport to close the describing equations at some level. It is widely understood that the theoretical basis for gradient transport is tenuous at best in most flows of practical interest. Under the extreme conditions of turbulent flames, involving as they do large value for the mean rate of strain as a result of heat release, the gradient approximation appears of even further dubiety. Therefore, it seems important to develop an alternative theory of premixed combustion, free of gradient approximations; reference 1 is a start in that direction.

At the present time a further development of the new theory is underway. Incorporated in the new study will be assessments of the importance of mean pressure gradient, i.e., of $d\bar{p}/dx$ for normal flames, and of the pressure fluctuations. In our previous studies both effects are neglected. There are suggestions, however, in particular from our experimental results on helium-air mixing in which counter-gradients of helium are found, that even weak pressure gradients can be significant when density variations exist. It must be acknowledged that our modeling of the terms involving pressure fluctuations will be highly speculative since such modeling even for constant density flows is subject to considerable discussion; for the variable density flows of interest to us, the modeling will be even more suspect. Nevertheless, plausible modeling should provide an indication of the importance of these effects. The final equations are now in hand and numerical analysis will proceed.

In the course of our studies of the new theory two significant conceptual developments have evolved. Bray has recently shown that in premixed combustion involving infinite turbulent Reynolds and Damkohler numbers, the case we have consider in our studies and at the same time of practical interest, the scalar dissipation χ is simply related to the mean rate of production of product, i.e., $\chi \propto \bar{w}$. The implication of this relation is that the model we and others have used for the scalar dissipation, taken as it is from

non-reacting flows, is probably incorrect and that a model more closely reflecting chemical effects should be used.

A physical explanation for this relation resides in the notion of laminar flamelets of thickness ℓ_ℓ which provide the sole source of the gradients of product concentration but which appear only a fraction γ of the averaging time. If we extend this physical notion further, we find that

$$\chi \propto u_\ell \, \tilde{c}(1-\tilde{c})/\ell$$

where $\tilde{c}$ is the mean product concentration, u_ℓ is the laminar flame speed for the same flow and chemical conditions as prevail for the turbulent flame in question, and ℓ is a length scale associated with the spacing of the laminar flamelets. This relation contrasts with

$$\chi \propto \tilde{q}^{1/2} \, \tilde{c}(1-\tilde{c})/\ell$$

which we and others have used; $\tilde{q}$ is the turbulent kinetic energy. The interesting point is that an important quantity determining the predicted behaviour of premixed flames now involves explicitly the laminar flame speed u_ℓ and is based on a simple physical picture of the reaction zone. A short technical paper setting forth these ideas is being prepared.

In our previous progress report we noted that we were preparing for another experiment involving a two-dimensional jet of helium discharging into a moving airstream, in this case with the helium heated, so that we deal with the two scalars. That experiment has been carried out and the reduction of data is well underway.

A review of our experimental work on helium-air mixing (reference 2) will be presented at the Dynamic Flow Conference 1978 at Johns Hopkins University, September 18-21, 1978.

References

1. Libby, P.A., A Non-Gradient Theory for Premixed Turbulent Flames. Mechanics Today 5 (accepted).

2. Libby, P.A. and LaRue, J.C., Hot-Wire Anemometry for Turbulent Measurements in Helium-Air Mixtures. Presented at and, to appear in the Proceedings of Dynamic Flow Conference 1978, Johns Hopkins University, September 18-21, 1978.

RESEARCH ON TURBULENT MIXING

California Institute of Technology, Pasadena, California
Subcontract No. 8960-1

Professor A. Roshko, Principal Investigator
Prof. P.E. Dimotakis, Co-Investigator
Mr. Luis P. Bernal, Research Assistant
Mr. Daniel B. Lang, Research Assistant

Introduction

It was discovered several years ago that turbulent mixing layers are dominated by large, organized, quasi two dimensional vortices or rollers, whose evolution and interactions dominate the development of the layer and control the gross mixing or engulfment of fluid from the two sides of the layer. Of course, turbulent flow could not be strictly two dimensional at high Reynolds number (because the necessary dissipation could not be provided), but there has been considerable controversy as to how the three dimensionality develops. One school (Ref. 1) holds that there will be a complete "breakdown" of any organized structures. Our own views, based on the experience in this laboratory (Refs. 2, 3, 4) and others, is that the existence of the organized structures has been demonstrated up to very high Reynolds numbers, that the tendency to organize characteristic structures is a basic property of the underlying mean vorticity distribution, and that the important three dimensional development is that of secondary and smaller scale motions superimposed on the main large ones. In Refs. 3 and 4 it was shown that no change in the large structure and in the gross development of the flow occurs when smaller scale structure develops at increasing Reynolds number. The amount of fluid engulfed is not increased. The main result is to increase the internal mixing, i.e., the extent to which the intimate molecular mixing is completed. Larger spanwise irregularities and departures from two dimensionality also occur but it does not appear that these make a major contribution to mixing at either the large scale or the small scale.

Discussion

One of the purposes of our present research program is to put the above observations on a firmer basis quantitatively. Some progress has been made in a parametric study of the streak pattern which appears in plan view pictures of the mixing layer; the streaks are thought to delineate secondary instabilities which produce streamwise vorticity, i.e., the first manifestations of three dimensionality and of the vortex stretching required for dissipation at increasing Reynolds number. The picture also suggests a further instability and breakdown of these streamwise streak patterns to smaller scales; the streamwise position at which this occurs corresponds to the position where the increase in internal mixing was observed by Konrad (Ref. 4).

To supplement these visual observations and to obtain quantitative definition of three dimensional effects in general we have modified our flow apparatus to deploy two of the concentration sampling probes at selectable spanwise separations from each other. (Concentration, or any passive contaminant, provides a more localized and sensitive measurement of spatial structure than does a velocity measurement.) For example, the probes can be located at predetermined positions with respect to the known streak patterns, e.g., one at a valley and the other at a crest. The experiment is controlled by our data acquisition system, which is being used to synchronize the probe data with fast framing rate, shadow or schlieren movies of the flow, so that the characteristic signature from the probe output can be correlated with structural features of the flow. An example of simultaneous outputs from two probes in a helium-nitrogen mixing layer is shown in Figure 1. The probes were located at the same coordinate streamwise and normal to the mixing layer but separated spanwise by a distance equal to about half a thickness of the shear layer at that position; one probe is at a "crest" and the other at a "valley" of the streak pattern. It is remarkable that, at such a small spanwise separation, there are such large occasional differences between the two signals. We believe them to be associated with the small scale secondary motions. To interpret the differences between these traces it is necessary to compare them with the simultaneous visual data, as explained above. The procedures for characterizing and correlating these signals and movies are now being developed. It is interesting that various mean values at the two locations, for example probability density functions, do not show much, if any, significant differences.

In a brief experiment on interference effects on the large structures, we placed splitter plates in the mixing layer at various downstream positions and observed the effects on shadow and schlieren pictures. The splitter plates were full span, of chord length equal to a few shear layer thicknesses, and were positioned in the central plane of the layer. Surprisingly, these produced no discernible effects on the development of the mixing layer. We were especially interested in upstream effect but could detect none.

In another brief experiment, a two point laser doppler anemometer system was used to make simultaneous velocity measurements at two points in the upper and lower edges of a mixing layer, respectively. From these the circulation of the large vortex structures was determined and found to agree well with calculations based on the observed vortex spacing, using a two dimensional theory. The good agreement seems to confirm the basically two dimensional nature of the flow. The experiment was carried out in the water channel described in Ref. 5.

Notes and References

1. Chandrsuda, C., Mehta, R.D., Weir, A.D. and Bradshaw, P., 1978, "Effect of Free-Stream Turbulence on Large Structure in Turbulent Mixing Layers," Journal of Fluid Mechanics, 85, 693.

2. Brown, G.L. and Roshko, A., "On Density Effects and Large Structure in Turbulent Mixing Layers," 1974, Journal of Fluid Mechanics, 64, pp. 775-816.

3. Rebollo, M., "Analytical and Experimental Investigation of a Turbulent Mixing Layer of Different Gases in a Pressure Gradient", Ph.D. Thesis, California Institute of Technology, 1973.

4. Konrad, J.H. 1976, "An Experimental Investigation of Mixing in Two-dimensional Turbulent Shear Flows with Applications to Diffusion-limited Chemical Reactions. Project SQUID Tech. Report CIT-8-PU.

5. Dimotakis, P.E. and Brown, G.L., 1976. "Large Structure Dynamics and Entrainment in the Mixing Layer at High Reynolds Numbers," Journal of Fluid Mechanics, 78, 535.

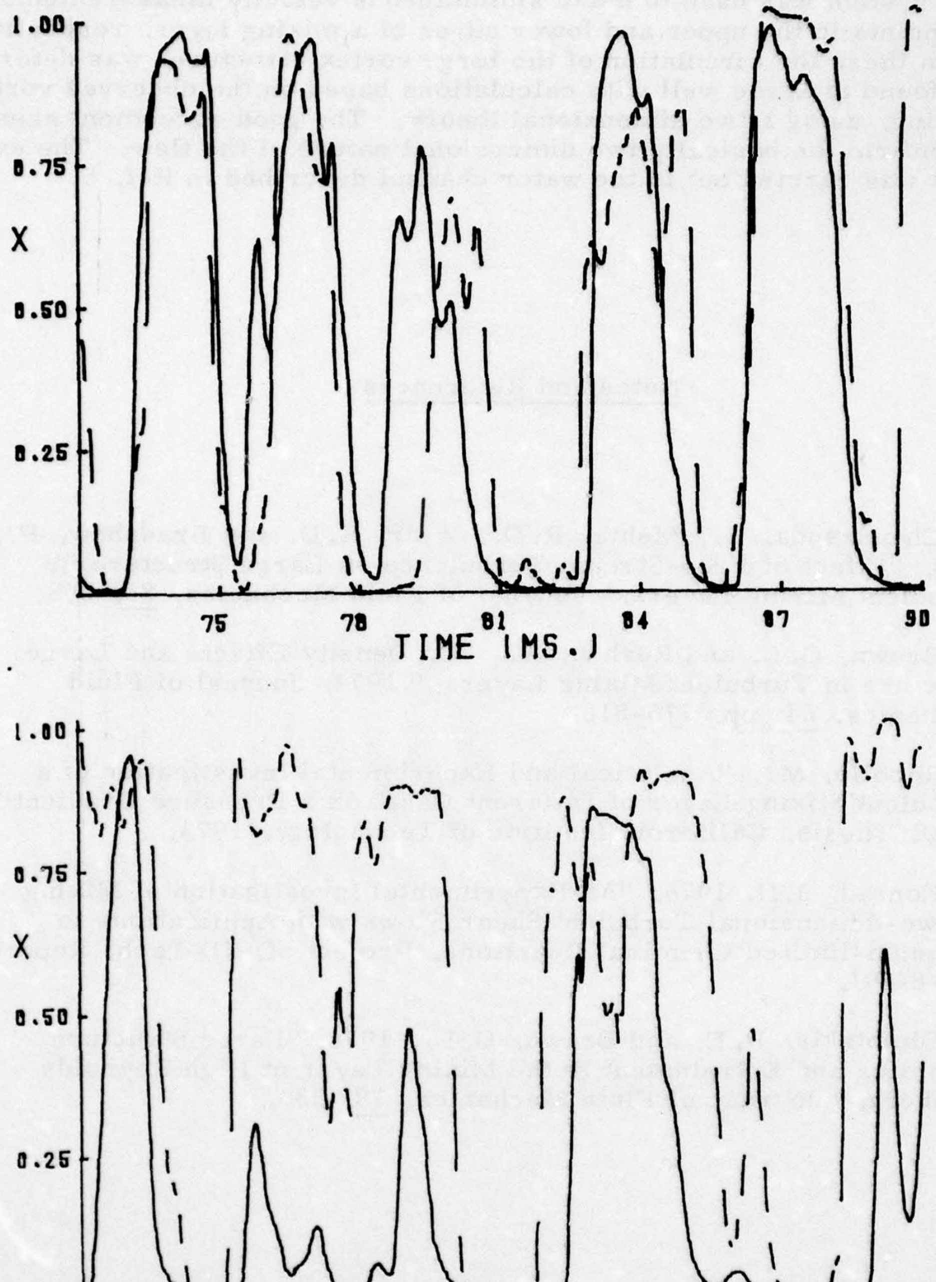

1.00
0.75
X
0.50
0.25
75
78
81
84
87
90
TIME (MS.)
1.00
0.75
X
0.50
0.25
93
96
99
102
105
108
TIME (MS.)

Figure 1

AD-A061 107 PURDUE UNIV LAFAYETTE IND PROJECT SQUID HEADQUARTERS F/G 21/8

PROJECT SQUID.(U)

OCT 78 T C ADAMSON, M SICHEL, E P BRUCE N00014-75-C-1143

UNCLASSIFIED NL

2 OF 2

ADA

061107

END

DATE

FILMED

1 -79

DDC

SWIRLING HEATED TURBULENT FLOWS
AS RELATED TO COMBUSTION CHAMBERS

University of Colorado, Boulder, Colorado

Professor M. S. Uberoi, Principal Investigator

Axial flows in trailing vortices. Axial flow in the core of a laminar steady trailing vortex from the tip of a semi-infinite wing is analyzed assuming small departure of the axial velocity from the free-stream velocity. It is further assumed that the axial pressure gradient is determined by the swirl velocities of an ideal infinite line vortex in which the radial and the associated axial velocity variations are neglected in the equation for the angular momentum. The axial and lateral variations of the axial velocity depend on the strength of the vortex and initial axial velocity distribution which must be specified at some station behind the wing except at the virtual origin of the vortex where a non-integrable singularity exists. Numerical solutions for the axial velocity are obtained using the axial pressure gradient given by the line vortex and analytical solutions are obtained using an equivalent axial pressure gradient with good agreement between the two sets of axial velocity distributions. Resolution of the previous uncertainties in this field is given which were due to the unrecognized singularity at the virtual origin of the vortex. Using the calculated axial velocity we determine the neglected radial and the associated axial fluxes of angular momentum and give the limits of validity of the theory presented here in terms of a suitably defined vortex Reynolds number and a nondimensional distance measured from the virtual origin of the vortex.

SECOND-ORDER CLOSURE MODELING OF TURBULENT COMBUSTION

Aeronautical Research Associates of Princeton, Inc.
Princeton, New Jersey
Subcontract No. 8960-26

Ashok K. Varma, Principal Investigator
Guido Sandri
Peter J. Mansfield

Introduction

Turbulent flows involving chemical reactions are a basic feature of many combustion and propulsion systems. The interaction between turbulence and chemistry is of considerable importance in determining combustion efficiency, pollutant formation, combustion noise, heat transfer, etc. Second-order closure modeling of turbulent reacting flows provides a convenient framework for studying these interactions between turbulence and chemical reactions, and this research program is directed toward the development of such a second-order closure procedure.

Models for the scalar probability density function (pdf) have to be developed to achieve closure of turbulent transport equations for mixing and reacting flows. We have developed a delta function "typical eddy" model for the joint pdf of the scalar variables that appears to provide good representation of actual pdf's in two-species, variable density mixing flows and is more than adequate for closure of the transport equations.

Discussion

The results of this research effort have been discussed in detail in a technical report that has been submitted to Project SQUID for distribution (Varma et al., 1978).

The statistical behavior of scalar variables in turbulent flows has been studied in the course of this investigation. It has been

proven that extremums of the allowed statistical bounds can only be attained by delta function pdf's. Continuous pdf's alone, that is, without delta functions are not sufficient, and can be statistically invalid. It has also been shown that the specification of a number of lower-order moments leads to rigid constraints on the higher-order moments. The constraints become significantly tighter as more lower-order moments are specified.

During the period covered by this progress report we have completed the development and testing of the "typical eddy" model for two-species mixing flows. We have proven that a physically realizable, rational pdf composed of a set of delta functions can always be constructed at every point within the statistically valid moment space. The delta function "typical eddy" model has been directly tested by comparison to the detailed pdf measurements of Konrad (1976) in three shear layer flowfields. A consistent procedure for the selection of the free parameter in the model has been established. It has been shown that the empirical concept of using the minimum entropy of mixing to calculate the free parameter, α_3 , leads to the best overall agreement with experimental data. Some features of the data, namely the prediction of third moments, are more accurate with the use of a value of α_3 at the middle of its allowed range, but the prediction of other experimental results is not as good with this model and we recommend the minimum entropy of mixing procedure as it is simpler and sufficiently accurate for providing closure of the transport equations. When four lower-order moments are specified, the model is able to calculate third-order moments to better than 10% accuracy, that is, significantly better accuracy than the expected experimental error-bounds. It appears unnecessary to construct more complex pdf's for the purpose of closure of transport equations in a second-order closure model.

The delta function pdf model has been incorporated in our second-order closure computer program, and complete second-order closure calculations of variable density mixing flows are currently underway. The development of the pdf model for reacting flows has also been started following the procedure established during the development of the two-species model.

References

Konrad, J. H. (1976): An Experimental Investigation of Mixing in Two-Dimensional Turbulent Shear Flows with Applications to Diffusion-Limited Chemical Reactions. Project SQUID Technical Report CIT-8-PU.

Varma, A. K., Sandri, G., and Mansfield, P. J. (1978): Modeling of Scalar Probability Density Functions in Turbulent Flows. Project SQUID Technical Report, also A.R.A.P. Report No. 352, Aeronautical Research Associates of Princeton, Inc., Princeton, New Jersey.

V. INDEX BY CONTRACTOR

INDEX BY CONTRACTOR

APPENDIX A

TECHNICAL REPORTS

SQUID TECHNICAL REPORTS ISSUED SINCE 1 APRIL 1978

SQUID NUMBER	TITLE AND AUTHOR(S)	ADA NUMBER
PU-R1-78	Engine-Airframe Integration (Short-Haul Aircraft) Proceedings of a Project SQUID Workshop, Edited by S.N.B. Murthy, Published April 1978.	ADA053417
UMO-3-PU	Shock Tube Studies of Formaldehyde Pyrolysis by A.M. Dean, B. L. Craig, R. L. Johnson, M. C. Schultz and E. E. Wang. April 1978.	A053695
UCSD-10-PU	Effects of Finite Reaction Rate and Molecular Transport in Premixed Combustion by P. A. Libby, K.N.C. Bray and J.B. Moss. May 1978.	ADA055629
UC-2-PU	Axial Flow in Trailing Line Vortices by M.S. Uberoi, Bhimsen K. Schwamoggi and Sin-Sung Chen. May 1978.	ADA057075
MIT-90-PU	Experimental and Theoretical Studies of Chemical Dynamics and Instabilities in Irreversible Processes by John Ross. August 1978.	ADA058855
ARAP-1-PU	Modeling of Scalar Probability Density Functions in Turbulent Flows by Ashok K. Varma, Guido Sandri, Peter J. Mansfield. (August 1978).	in process
MSU-1-PU	An Experimental Study of the Transport of a Non-Diffusive Scalar Contaminant in the Decaying Turbulence Field of an Enclosed Chamber by K.C. Cornelius and John F. Foss. (August 1978).	in process

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER Semi-Annual Report	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Project SQUID Semi-Annual Progress Report 1 October 1978	5. TYPE OF REPORT & PERIOD COVERED Semi-Annual 4/1/78-9/30/78
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) T. Adamson F. Carta A. Dean F. Gessner F. Browand H. Calcote A. Eckbreth J. Johnston E. Bruce N. Chigier J. Fenn M. Lapp S. Lederman W. McLean W. Sadeh M. Uberoi T. Lester W. O'Brien R. Simpson A. Varma P. Libby A. Roshko W. Sirignano	8. CONTRACT OR GRANT NUMBER(s) N00014-75-C-1143 NR-098-038
~~9. PERFORMING ORGANIZATION NAME AND ADDRESS~~	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Power Program, Code 473 Department of the Navy, 800 No. Quincy Street Arlington, Virginia 22217	12. REPORT DATE 1 October 1978
	13. NUMBER OF PAGES 118
~~14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)~~ 9. Performing Organization Project SQUID Headquarters, Purdue University Chaffee Hall, West Lafayette, Indiana 47907	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

This document has been approved for public release and sale; its distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Semi-Annual
Aerodynamics and Turbomachinery
Combustion and Chemical Kinetics
Measurements
Turbulence

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Reports of progress during the past six months on the 23 research programs comprising Project SQUID are presented. The research programs fall into the areas of Aerodynamics and Turbomachinery, Combustion and Chemical Kinetics, Measurements and Turbulence. Project SQUID is a cooperative program of basic research related to jet propulsion. It is administered by Purdue University and sponsored by the Office of Naval Research.